

REPORT NO.
UA-GC-24/01

UAlberta Geotechnical Centre

**CENTRIFUGE MODELING OF AXIAL
COMPRESSIVE LOADING TESTS OF
HELICAL PILE GROUPS IN SAND –DATA
REPORT FOR NI03**

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DATE: 09 FEBRUARY 2024

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Centrifuge Modeling of Axial Compressive Loading Tests of Helical Pile Groups
in Sand –

Data Report for NI03

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Report Date: January 20, 2023
Testing Date: November 29, 2023- December 15, 2023
Research Project: Axial Behavior of Helical Piles and Pile Groups in Sand:
Centrifuge Modeling and Numerical Simulations
Award number: CRDPJ 543483 -19
PI: Lijun Deng; Co-PI: Rick Chalaturnyk
Sponsor(s): Natural Sciences and Engineering Research Council of Canada
(NSERC) and Reaction Screw Piling Inc. (RSP)
Preceding Documents: Test Program- 21/02/01 , SOP-22/11/13

Acknowledgements

The centrifuge model test was funded by NSERC and RSP. The authors would gratefully acknowledge the assistances of Yazhao Wang, Dmytro Pantov, and Chunhui Liu from the University of Alberta (UAlberta).

The model tests were performed using the GeoCERF centrifuge lab facilities at UAlberta. The development of the Centrifuge (GeoCERF) facility was supported by the Canadian Foundation for Innovation.

Conditions and Limitations

Permission is granted for the use of these data for publication in the open literature. It is essential that the authors and sponsors be consulted prior to publication to discuss errors or limitations in the data not known at the time of the release of this report. There may be later releases of this report. Questions any regarding the report may be directed by email to ldeng@ualberta.ca.

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1 Introduction

The test program NI03 is the third and last part of the test series aimed at the study of the axial group pile behavior of helix piles in sand using the centrifuge modeling technique. The specific objectives of the test series are: 1) Implement a group loading mechanism followed by axial loading on the grouped pile; 2) Investigate the effect of helices and batter angle on the axial responses within the group piles; and 3) Investigate the effect of the group on the axial load distribution and internal load transfer mechanism within the piles. All the model piles and pile caps were fabricated with aluminum. In general, there are two pile types, designed as P3 for the helix pile and P0 for the smooth pile. The P3 is a double helix pile with the inter helix spacing ratio of 2.5 times the helix diameter. The shaft diameter, d , was kept 12.7 mm (0.5 in), the helix diameter, D , was 38.1 mm (1.5 in), and the embedment of the piles was 150 mm. The pitch of a helix defined as the opening size of the helix of 12.7 mm was set to be scaled from the pitch size of a prototype pile at 190.5 mm. Table 2 lists the dimensions of all the model piles. Fig. 1 shows the schematics of the model piles. The dimensions were determined from prototype piles in practice.

Three types of pile groups of four and two were fabricated that varied in battering of angles ($\beta = 0^\circ, 10^\circ$ and 20°) of piles in the cap. The design of pile caps with provisions to test for variable spacing and batter angles is detailed in Appendix A.

Four separate model soil box was prepared with silica sand (Sil-3) supplied by Sil Industrial Minerals in Edmonton, Alberta. The model sand box was freshly prepared each time for testing with air pluviation of sand using a portable travelling pluviator (PTP). The relative density of the deposited sand was estimated from the developed calibration chart relating to the height of fall of sand in the model box and later verified with small container method. Axial and Bending strain gauges were installed separately at various sections of the consecutive piles in a group to measure the axial load and bending moment distribution over the pile length. The piles were preinstalled 1 g level and later pluviated with sand. Hence, at the centrifuge setup, each of the pile groups were spun and loaded in monotonic compression inflight at 15 g scale units upto a normalized axial displacement of 10% of the helix diameter (for P3) or 20% of the shaft diameter (for P0); to assess the ultimate load capacity and bending moment of each pile in the group. It is to note that, the prior test series (NI01 and NI02) on single helix piles were tested at 20 g scale units. However, at 20 g scale, the group battered pile could not be tested due to exceedance of the capacity of the loading actuator gear motor. The readings were measured using an HBM Data Logger MX1615 B and later read through the computer program CATMAN.

Table 1. Dimensions of the model piles

Pile Code	Number of helices	S (mm)	S/D	L (mm)	d (mm)	D (mm)	P (mm)
P0	0	N. A.	N. A.	258	12.7	38.1	12.7
P3	2	95.2	2.5				

Note: S = spacing of two helices; d = shaft diameter; D = helix diameter; P = pitch of helix.

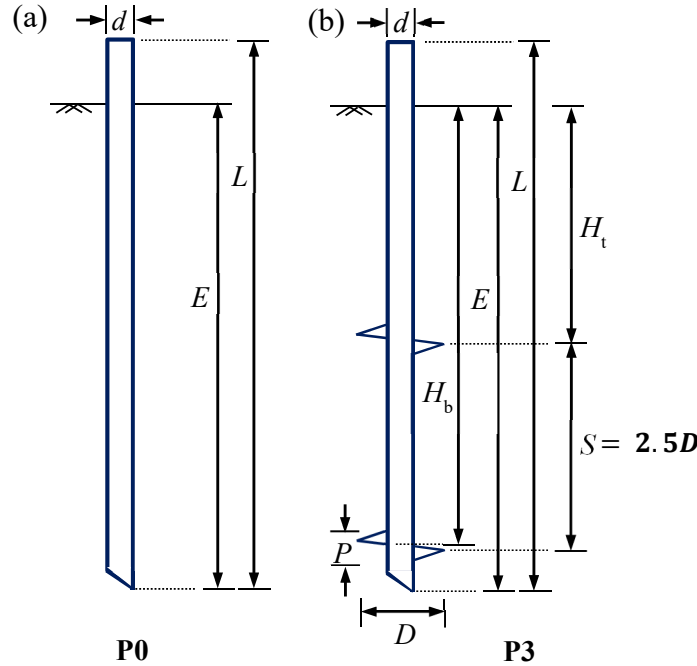


Figure 1. Schematic Diagram of the Model Helical Piles: (a) Smooth pile, P0 and (b) Helix pile, P3.

Tests were conducted on the 2-m- radius Broadbent centrifuge at UAlberta. Model scale factors of the analyzed parameter are listed in Table 2.

Table 2. Selected scale factors (prototype/model) of centrifuge modeling tests

Term	Force	Dimension	Stress
Scale Factor	225	15	1

2 Centrifuge Testing Program

2.1 Test matrix

Figure 2 shows the test layout plan and cross sections for NI03. It is divided into four parts, NI03a, NI03b, NI03c, and NI03d. Table 3 provides a summary of the test matrix. In NI03a, monotonic compression loads were applied on two groups of four piles where the first group consists of four-helix piles (4P3S3B0) with pile spacing ($s/D = 3$) and batter angle ($\beta = 0^\circ$) and in the second group four smooth piles (4P0S3B10) with pile spacing ($s/D = 3$ or $s/d = 9$) and batter angle ($\beta = 10^\circ$). The batter angles were set from the current industrial practices of helical pile grouping, with recommendations from the industrial partner and past studies.

In NI03b, monotonic compression loads were applied on two groups of four piles where

the first group consists of four-helix piles (4P3S2B0) with pile spacing ($s/D = 2$) and batter angle ($\beta = 0^\circ$) and in second group four-helix piles (4P3S3B10) with pile spacing ($s/D = 3$) and batter angle ($\beta = 10^\circ$).

In NI03c, monotonic compression loads were applied on one groups of four piles and one group of two piles, where the first group consists of four-smooth piles (4P0S2B10) with pile spacing ($s/D = 2$ or $s/d = 6$) and batter angle ($\beta = 10^\circ$) and in the second group two piles (2P3S2B20) with pile spacing ($s/D = 2$) and batter angle ($\beta = 20^\circ$).

In NI03d, monotonic compression loads were applied on one groups of four piles and one group of two piles, where the first group consists of four-helix piles (4P3S2B10) with pile spacing ($s/D = 2$) and batter angle ($\beta = 10^\circ$) and in the second group with two-helix piles (2PS3B20) with pile spacing ($s/D = 3$) and batter angle ($\beta = 20^\circ$).

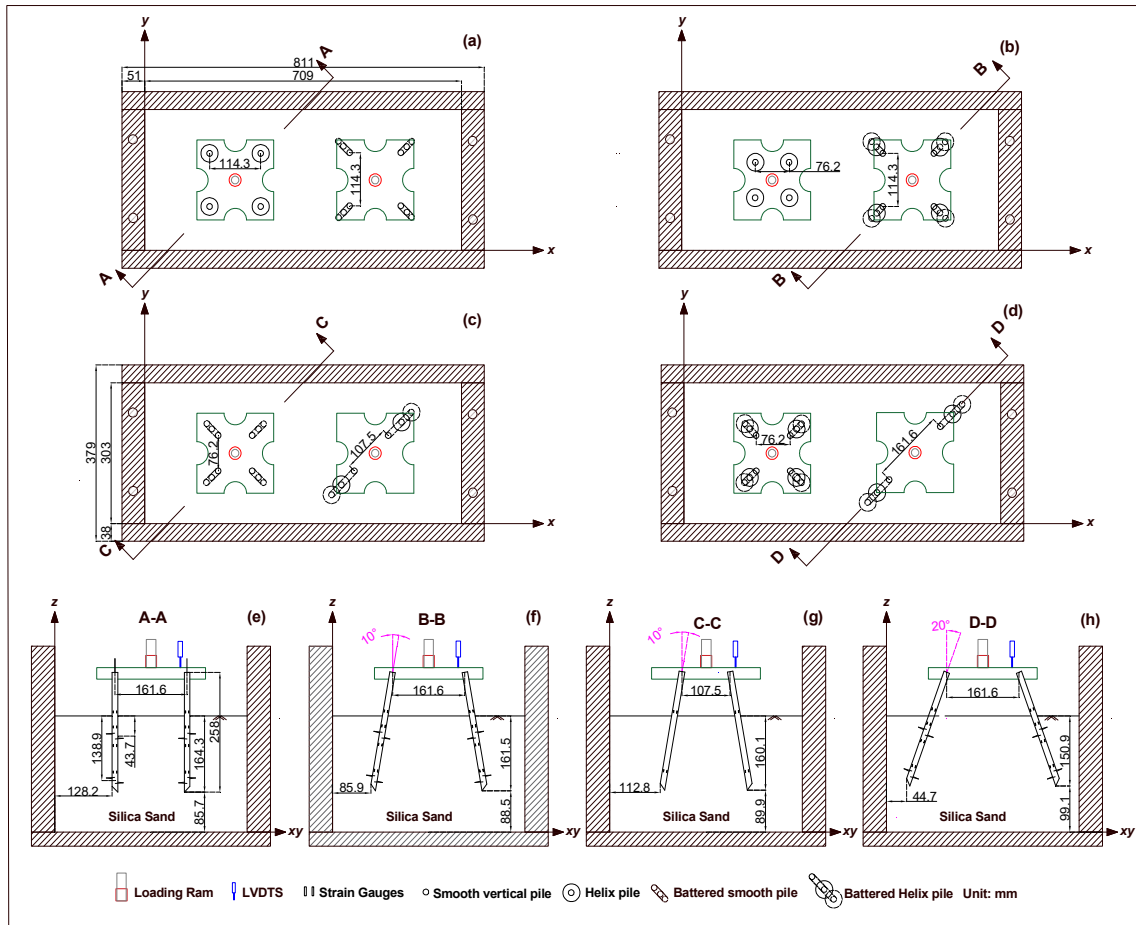


Figure 2. Centrifuge Test Layout plan: (a) NI03a; (b) NI03b; (c) NI03c; (d) NI03d; Cross-sectional profile at (e) A-A section; (f) B-B section; (g) C-C section and (h) D-D section. All dimensions are in model scale.

Table 3. Summary of test matrix for NI03 series

Test Plan	Test ID*	Number of piles in groups	Number of Instrumented Piles in Group	Number of Soil Model Boxes
NI03a	4P3S3B0	4	3	1
	4P0S3B10	4	3	
NI03b	4P3S2B0	4	3	1
	4P3S3B10	4	3	
NI03c	4P0S2B10	4	3	1
	2P3S2.8B20	2	2	
NI03d	4P3S2B10	4	3	1
	2P3S4.2B20	2	2	

*Note: The group piles are designated as **GPXSYBZ**, where, **G** = number of pile in the group, **P** = pile, **X** = pile type number, **S** = spacing of two helices with respect to helix diameter, **Y** = pile spacing with respect to helix diameter, **B** = Battering of Piles, **Z** = value of Batter angle.

2.2 Soil Properties

The model test was performed upon dry silica sand (Sil-3) supplied by Sil Industrial Minerals in Edmonton, Alberta. The geotechnical properties of Sil-3 sand are summarized in Table 4. The minimum and maximum density of the Sil 3 sand was measured following ASTM D4254-16 and ASTM D4253-16e1 respectively. The tested particle size distribution (PSD) of Sil-3 sand is shown in Fig. 3. From the PSD, the estimated, $d_{50} = 0.29$ mm, $C_u = 1.5$ mm and $C_c = 1.08$ mm, indicates uniform distribution of grain sizes. As per Schiavon et al. 2016, effective model sand for centrifuge test of helix piles should carry uniformly distributed grain sizes, should not contain a lot of fine sand dust and maintain the ratio of the effective helical radius of the model helix piles (r_h) to the average grain size (d_{50}) of the sand, r_h/d_{50} greater than 58. Hence, for Sil- 3 as model sand, the r_h of the model piles was kept greater than 16.82 mm (discussed in the following section). The direct shear test on the Sil-3 sand is shown in Fig. 4. Table 5 shows the estimated parameter for the direct shear test.

Table 4. Geotechnical properties of model silica sand

Term	Value
Specific Gravity (G_s) (Correlated)	2.65
Average Bulk density (ρ), Mg/m^3	1.61
Constant Volume Friction angle (ϕ_{cv}), $^\circ$	31.7
Maximum Dry Density ($\rho_{\max}$), Mg/m^3	1.73
Minimum Dry Density ($\rho_{\min}$), Mg/m^3	1.52
Minimum void ratio ($e_{\min}$)	0.53
Maximum void ratio ($e_{\min}$)	0.74

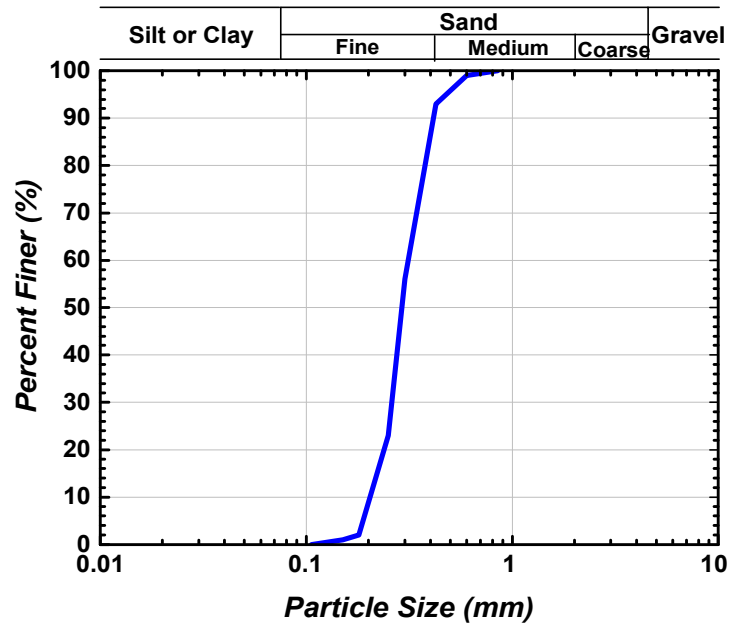


Figure 3. Particle size distribution of model silica sand.

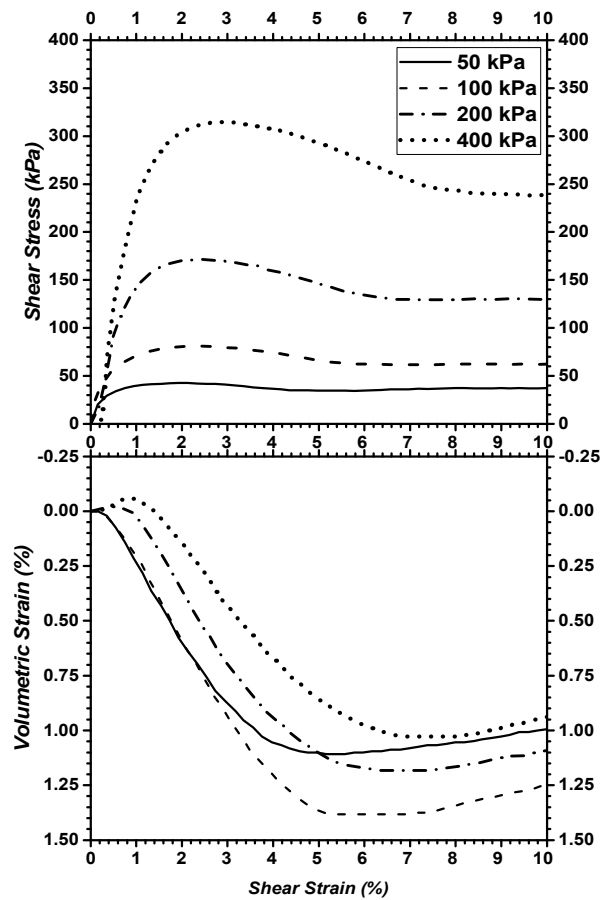


Figure 4. Direct Shear test results on Sil 3 Sand (strain rate: **0.76 mm/min**).

Table 5. Estimated Shear Strength parameters of Sil 3 sand from the direct shear test

Cohesion intercept condition	Estimated c' and ϕ'
With zero intercept for cohesion	$c' = 0 \text{ kPa}$ and $\phi' = 38.7^\circ$
	$c'_{cv} = 0 \text{ kPa}$ and $\phi'_{cv} = 31.2^\circ$
Without zero intercept for cohesion	$c' = 6.2 \text{ kPa}$ and $\phi' = 37.9^\circ$
	$c'_{cv} = 5.9 \text{ kPa}$ and $\phi'_{cv} = 30.8^\circ$

2.3 Soil model construction

The soil model was constructed in an aluminum container. The container measures internally, 709.2 mm (length), $\times 300 \text{ mm}$ (width) $\times 400 \text{ mm}$ (height) with wall thickness $\geq 30 \text{ mm}$. The box was designed for a maximum centrifugal acceleration of 50 g scale unit. To reduce the gross weight in-flight, all the walls were made of aluminum. The model sand deposition was controlled with a portable traveling pluviator (PTP) setup to allow uniform density deposition of sand at each layer in the model box.

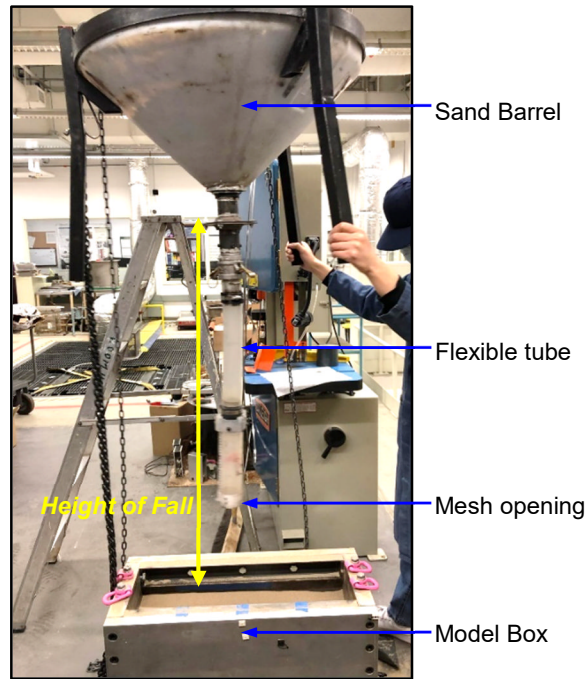


Figure 5. Portable traveling sand pluviator setup.

Figure 5 shows the various components of the portable travelling pluviator (PTP) setup for the Sil-3 sand deposition in the model box. The configuration of PTP is similar to the stationary/portable travelling pluviator (PTP) as reported in literature (e.g. Dave and Dasaka 2012, Gade and Dasaka 2016, Hakhamaneshi et al. 2016 and Taeseri et al. 2018). The height of fall and the mesh size can be adjusted to control the density of the sand in the model box. The PTP was used to calibrate the Height of Fall against the relative density, varying the deposition height between 110 -150 mm and changing the mesh size opening

for 5 mm and 100 mm. Figure 6 shows the calibration assembly for the PTP using a density mould.

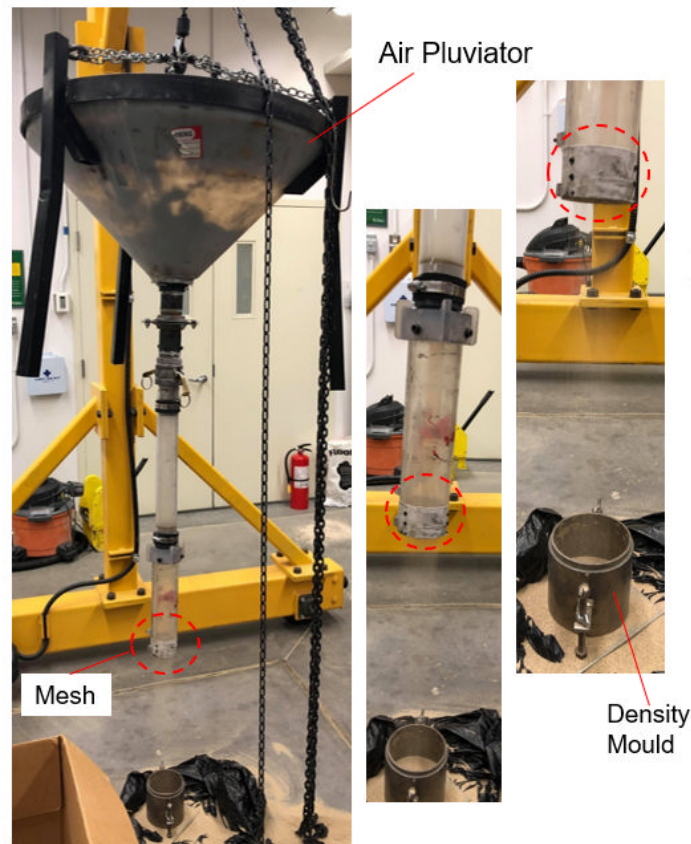


Figure 6. Calibration Assembly for the Portable Travelling Pluviator

Figure 7 presents the calibration chart developed to ascertain the relationship between the relative density of sand with the height of fall of sand from the PTP to the model box for mesh openings of 5 mm and 10 mm, respectively. The height of fall varied between 110 cm to 150 cm to deposit the sand in a density mold. Later, the relative density of sand for each calibration test was determined. As observed in Fig. 7, the relative density ranged between 72 to 100 % for 10 mm mesh opening and 46 to 86 % for 5 mm mesh opening. For test NI01, the relative density was fixed at 55%, which corresponds to a height of fall of 114 cm at the PTP. Figure 8 shows the schematic of the plan view of the model soil box showing the path of motion of the PTP during preparation of the sand bed.

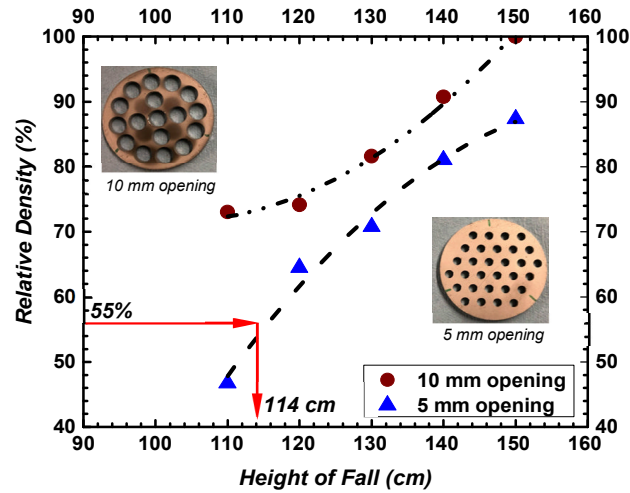


Figure 7. PTP calibration chart for the relationship between the relative density of sand with Height of fall for two mesh openings.

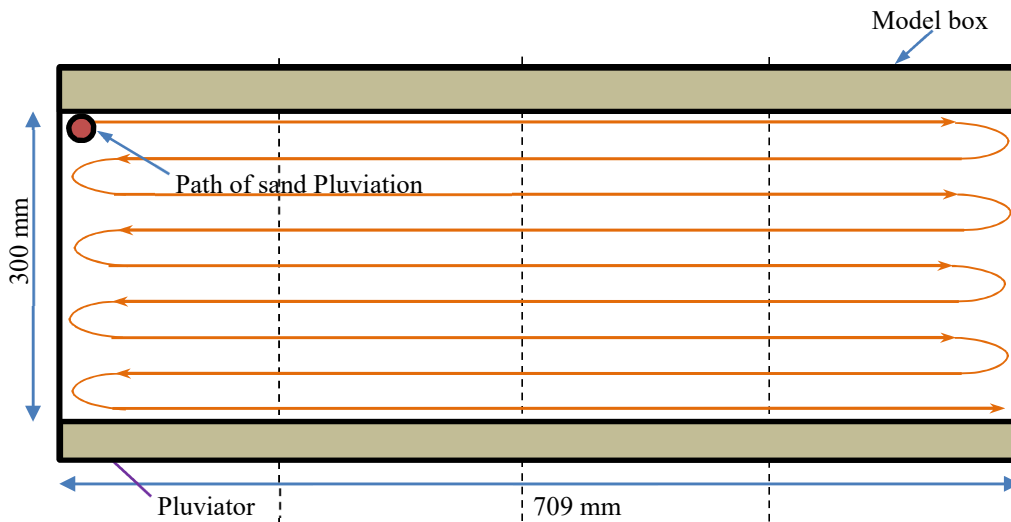
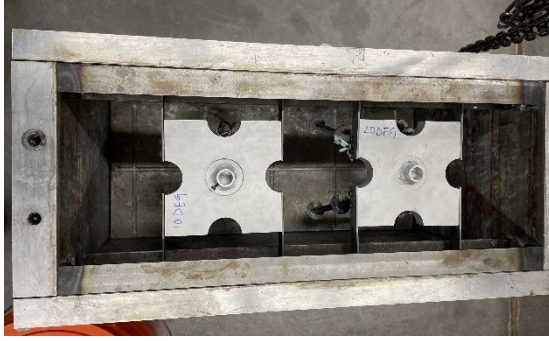
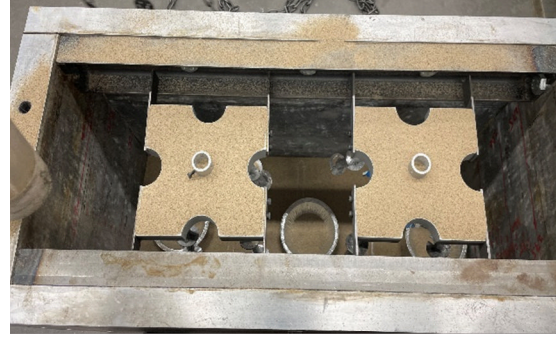


Figure 8. Plan view of plain strain model box showing path of sand Pluviation.

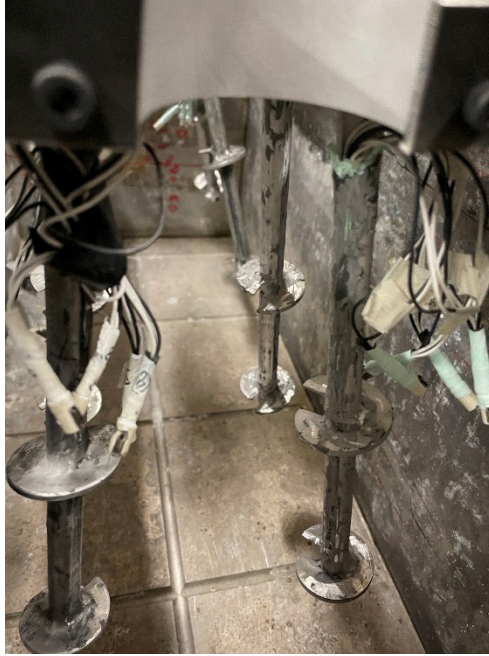
Figure 9 shows the photos of sand pluviation in the model box. The quality of deposition of sand in the model box was verified using the small container method (see Choi et al. 2010 and Tabaroei et al. 2017). A total of 12 small containers (four in each layer) were selected to estimate the density on it along the course of travel of the PTP maintaining a uniformity in the height.



(a) Plan view of the box with preinstalled pile caps



(b) Plan view of the ongoing Pluviation



(c) Side view of the preinstalled piles in the box



(d) Side view of ongoing pluviation with sand filling

Figure 9. Pluviation of sand in the model box.

The average relative density was measured from the weight of the strong box before and after the pluviation of sand (see in Table 6). The measured average relative density was 53.5% for an average soil bulk density of 1.62 gm/cm^3 .

Table 6. Deposition density of sand in the model box

Measured Quantities	NI03a	NI03b	NI03c	NI03d
Weight of empty strong box (kg)	133.0	133.0	133.0	133.0
Weight of strong box + sand (kg)	226.0	225.0	224.0	225.5
Weight of two pile cap and piles (kg)	5.0	5.0	5.0	5.0
Volume of sand in model box (m^3)	0.1	0.1	0.1	0.1
Density (gm/cm^3)	1.64	1.62	1.60	1.63
Relative Density (%)	61.1	52.5	43.6	56.8

2.4 Model Pile Instrumentation

In the present research, model piles (shown in Figure 10) are instrumented with axial and bending strain gauges for measuring the internal axial forces and bending moments during pile group loading tests. The gauge CEA-13-062UW-350 were ordered from the supplier Terracene International (made by Micro Measurements VPG) that are universal general-purpose type with strain ranges of $\pm 3\%$. Fig. 11 shows the configuration of the gauge.

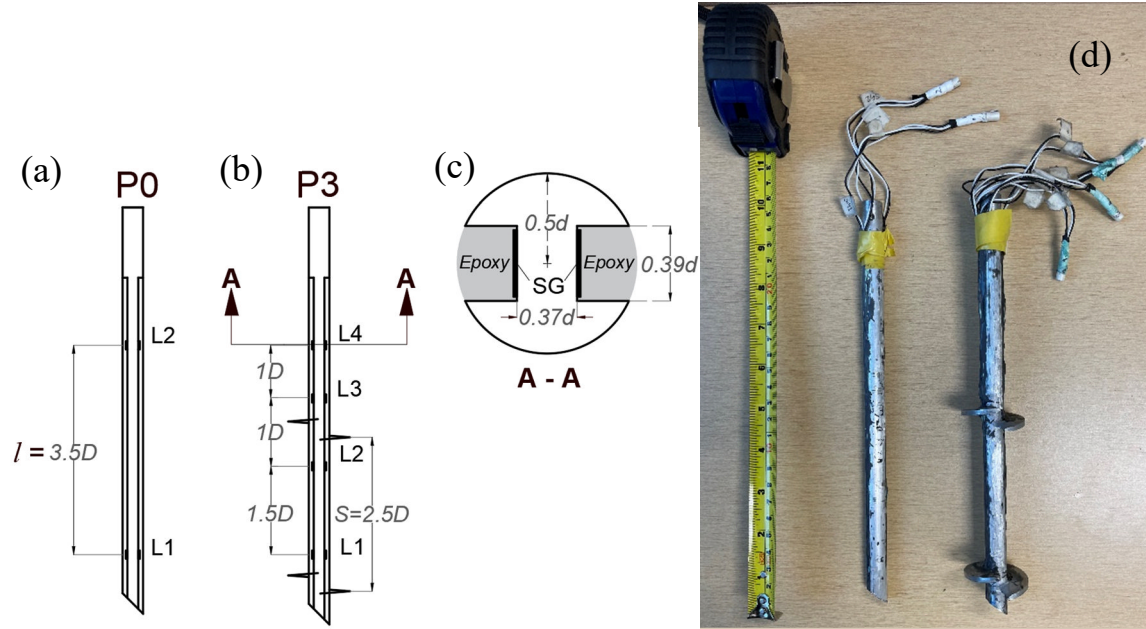


Figure 10. Location of Instrumentations on the model piles: (a) P0; (b) P3; (c) Cross section at the instrumentation location and (d) Photos of Instrumented piles.

As per the precision Strain Gauges handbook from the supplier, the terminologies: **CEA** indicates Universal general purpose strain-gages. Constantan grid completely encapsulated in polyimide, with large, rugged copper-coated tabs. The following number **13** (Item a) or **06** (Item b) designates the approximate thermal expansion coefficient in $\text{ppm}/^{\circ}\text{F}$ of the structural material on which the gage is to be used. The following number, **062** designates the active gage length in Mils [0.001 in (0.0254 mm)]. **UW** or **UV** stands for grid and tab geometry and the number at the end indicates the resistance in Ohms.

For both axial and bending strain measurement, a half Wheatstone bridge circuit consisting of two active single gauges will be adopted. The gauge model is CEA-13-062UW-350. The gauges are placed on two grooves cut into the pile shaft. The active gauges are wired to two dummy gauges on the data acquisition box. The locations of strain gauge stations are determined with the consideration of anticipated load distribution, so that the axial load transfer mechanism along the shaft and helical plates can be inferred.

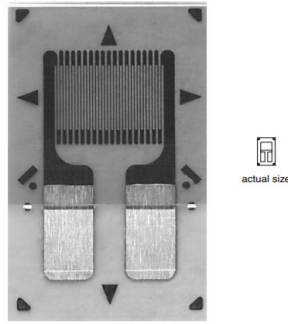


Figure 11. Strain Gauge, CEA-13-062UW-350

The arrangement of the approximate locations of the strain gauges are presented in Figure 12. In order to protect the strain gauges from any potential damages from moist invasion or physical abrasion, especially for these axial gauges embedded in soil, the following techniques are adopted:

- Two grooves, 5 mm wide and 4.75 mm deep, were excavated along the shaft on the opposite sides.
- Axial or bending strain gauges were then glued to the bottom of the grooves. To prevent moisture attack and electric leakage, the strain gauges were covered with VPG M-B coating and Teflon tapes, and then the grooves were carefully filled with epoxy (shown in Fig 12 a)
- The surfaces of the cured epoxy were eventually smoothed with a sanding tool and polished with soft cloth.

The summary of instrumentation on the model piles are shown in Table 7. Calibration of the strain gauges were performed using the HBM data logger MX 1615B to convert the electronic signals into engineering units. The analyzed results and setup for calibration are presented in Appendix B.

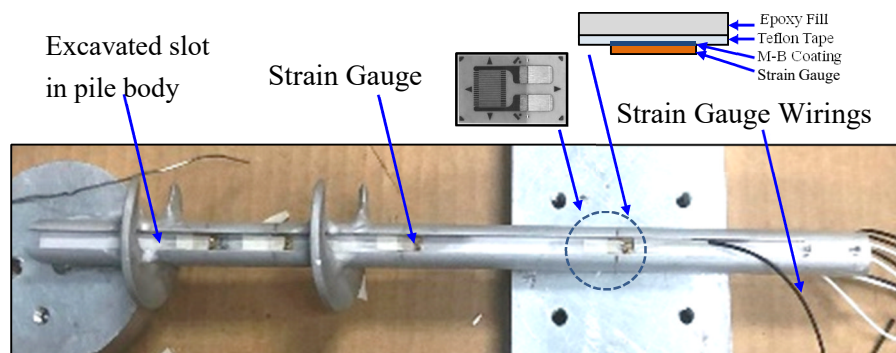


Figure 12. Approximate locations of strain gauge stations and protection technique.

Figure 13 presents the Wheatstone bridge connections for the axial and torque strain gauges as in the model connection assembly.

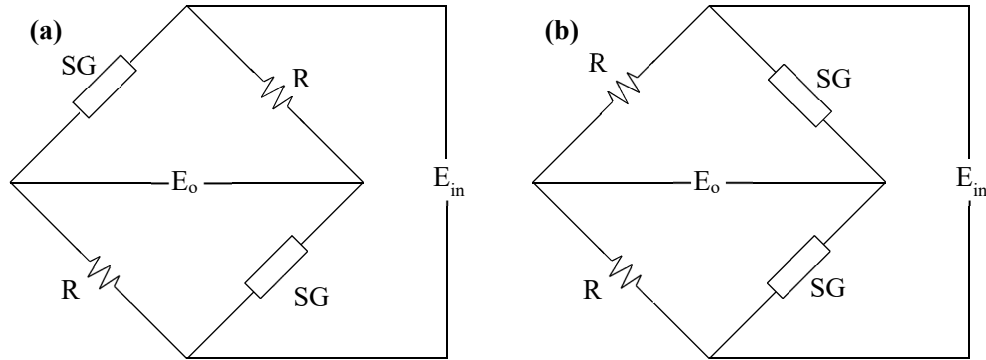


Figure 13. Half bridge circuit for (a) axial strain measurement and (b) bending strain measurement, where SG = axial strain gauge on pile shaft and R = complementary resistor embedded in the data logger.

Table 7. Summary of Instrumentation on the pile groups

Pile Group ID*	Number Axial Strain Gauges per instrumented pile	Number Bending Strain Gauges per instrumented pile	Number of LVDTs
4P3S3B0	8	16	2
4P0S3B10	4	8	2
4P3S2B0	8	16	2
4P3S3B10	8	16	2
4P0S2B10	4	8	2
2P3S2.8B20	8	8	2
4P3S2B10	8	16	2
2P3S4.2B20	8	8	2

*Note: The group piles are designated as **GPXSYBZ**, where, **G** = number of pile in the group, **P** = pile, **X** = pile type number, **S** = spacing of two helices with respect to helix diameter, **Y** = pile spacing with respect to helix diameter, **B** = Battering of Piles, **Z** = value of Batter angle.

Figure 14 shows the locations of the LVDT instrumentation for measuring the relative rotation of the pile cap with respect to the center cap.

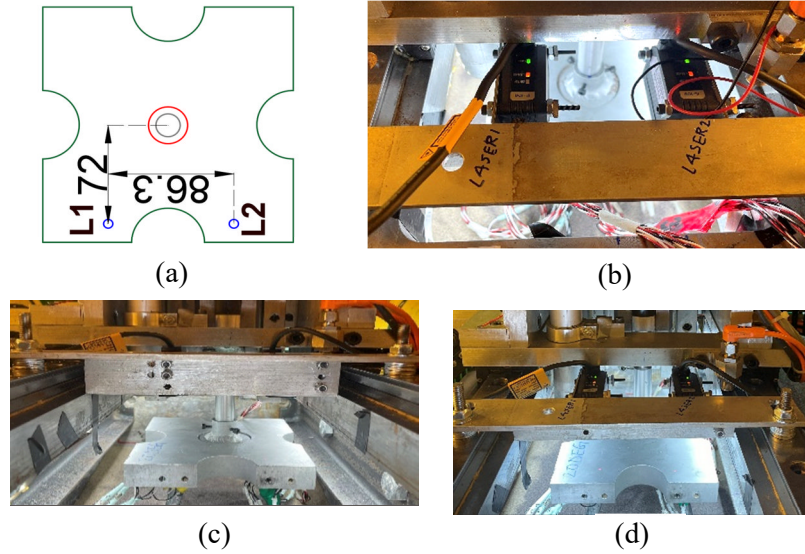


Figure 14. (a) Locations of the two Laser LVDTs (L1 & L2) on the pile cap; (b) Top view of the LVDT placement; (c) Side view of the LVDT placement; (d) Inclined view of the LVDT illuminating lasers over the definite locations on the pile cap.

2.5 Fabrication of Pile caps

Figure 15 shows the schematics and photo of the designed and fabricated model pilecaps. Appendix A shows the detail dimension and photos of the pilecaps. The pilecaps were made of Aluminum. The mass of each of the caps was 2 kilograms. The size and thickness of the pilecaps were designed to support a maximum of four pile groups in the model box. Appendix A contains further details on the dimensions of the individual pile caps for accommodating batter pile groups at different pile spacing. Provisions were also made on the pilecaps to accommodate a semicircular gap on all four sides to provide spaces for the sand air Pluviation on the model box.

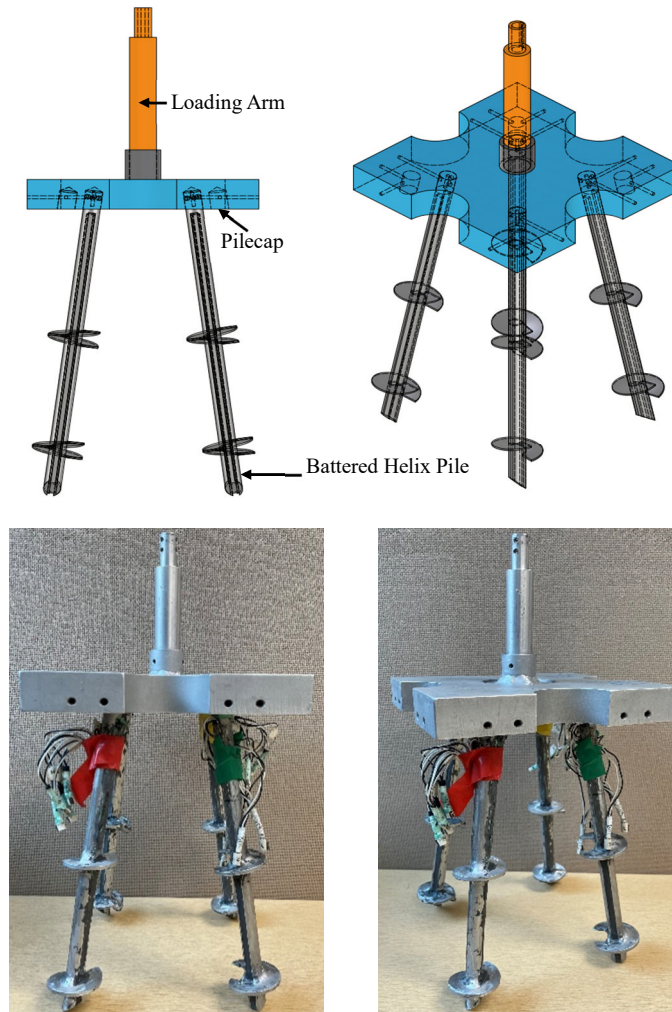


Figure 15. Batter Pile Group (a) Schematic Representation (b) Fabricated Model.

2.6 Centrifuge Model Box Configuration

Figure 16 shows the model assembly on the centrifuge with its various components. Figure 17 shows the schematics of the assembly and connection assembly to the control room for imposing loading and data logging.

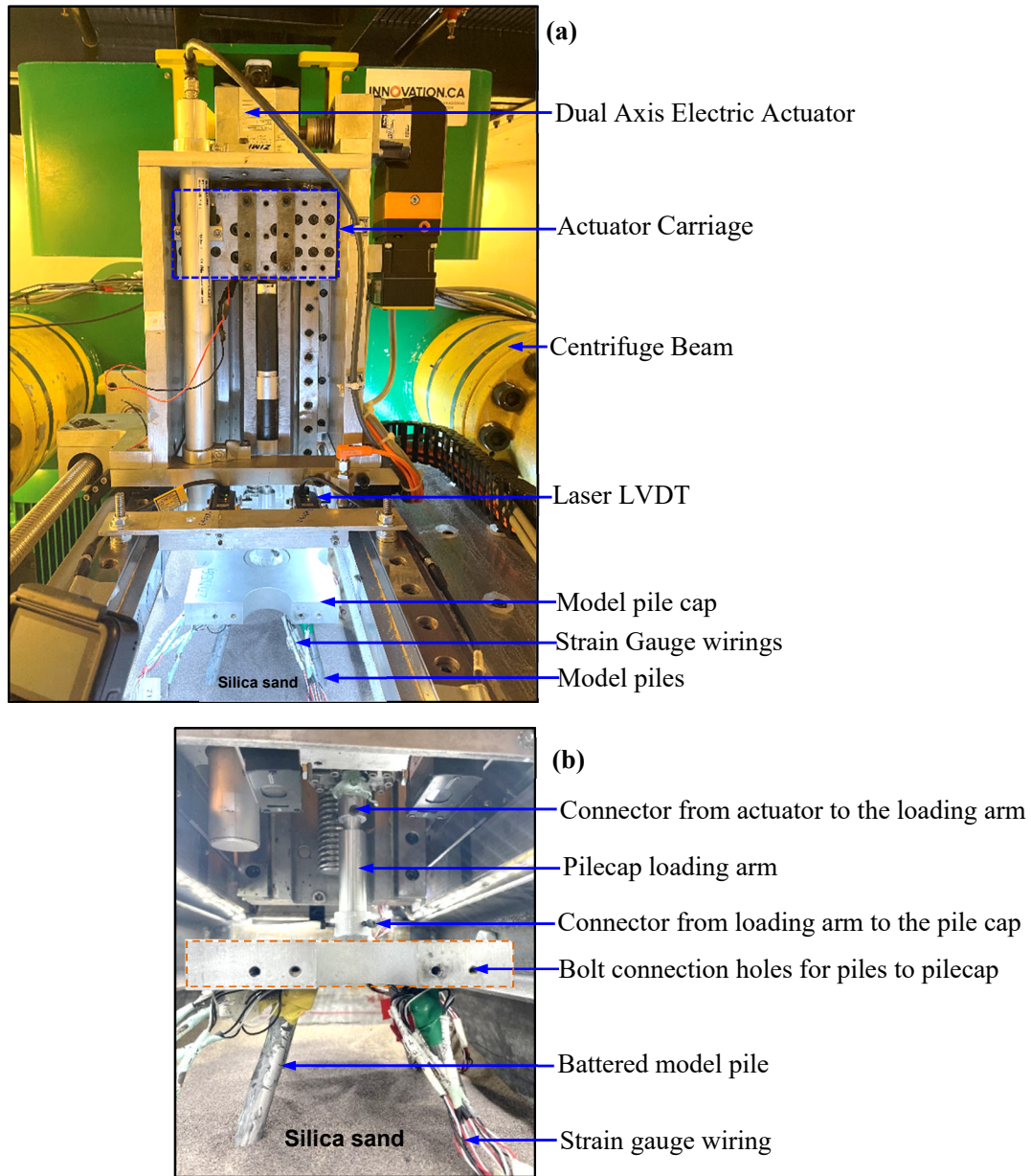


Figure 16. Centrifuge Model Assembly (a) Side view of the Loading Assembly; and (b) Side view of the preinstalled pile cap inside the model sand box.

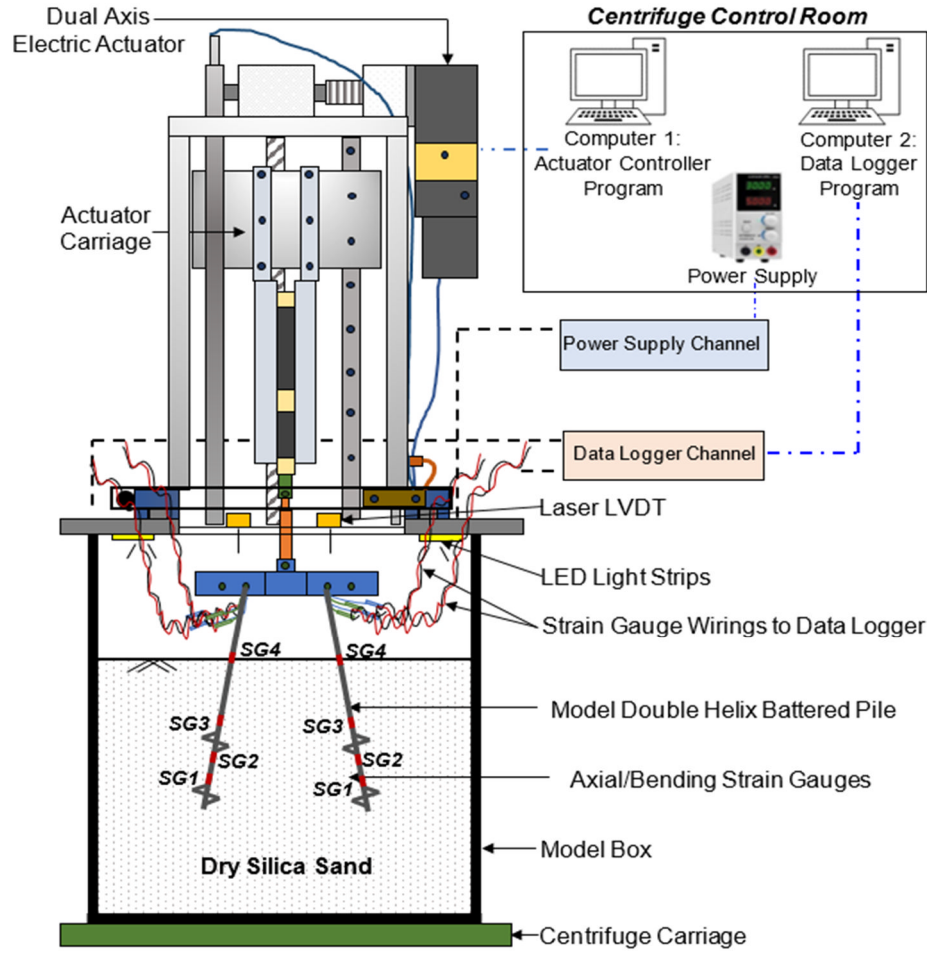


Figure 17. Schematic of Centrifuge Model Assembly.

3 Test and Loading Sequence

The test and loading sequence were arranged based on the test matrix. In the test sequence, the actions at each day with the time and date were recorded and presented in a tabular format. Table 8 shows the test sequence for NI03 test series.

Table 8. Test sequence for NI03 centrifuge model tests

Day Count	Date	Work/St	Action
1	29 Nov 23 Wednesday	1	Air pluviation of sand in model box for NI03a
2	30 Nov 23 Thursday	2	Lowering of model box in the swinging table and loading setup arrangement
3	1 Dec 23 Friday	3	Monotonic Compression tests on pile caps in NI03a and Uplifting of model box for NI03b.
4	4 Dec 23 Monday	4	Clear of sand from the model box and air Pluviation of sand in model box for NI03b

Data Report for NI03 Centrifuge Test Series

Day Count	Date	Work/St	Action
5	5 Dec 23 Tuesday	5	Lowering of model box in the swinging table and loading setup arrangement
6	6 Dec 23 Wednesday	6	Monotonic Compression tests on pile caps in NI03b and Uplifting of model box for NI03c.
7	7 Dec 23 Thursday	7	Clear of sand from the model box and air Pluviation of sand in model box for NI03c
8	8 Dec 23 Friday	8	Lowering of model box in the swinging table and loading setup arrangement
9	11 Dec 23 Monday	9	Monotonic Compression tests on pile caps in NI03c and Uplifting of model box for NI03d.
10	12 Dec 23 Tuesday	10	Clear of sand from the model box and air Pluviation of sand in model box for NI03d
11	13 Dec 23 Wednesday	11	Lowering of model box in the swinging table and loading setup arrangement
12	14 Dec 23 Thursday	12	Monotonic Compression tests on pile caps in NI03d and Uplifting of model box.
13	15 Dec 23 Friday	13	Bringing the model box up, Clear sand from the model box, retrieving all data, and test completion preparation

Each of the pile caps were installed at 0.76 mm/min at 15 g-level up to a maximum normalized displacement of 10% of the helix diameter or 20% of the shaft diameter.

4 Recorded Data

The data was recorded in HBM Data Logger and arranged on the folder titled Centrifuge Test NI03 in the format shown in Table 9.

Table 9. Organization of data files

Test ID	Data file	Description
NI03 4P3S2B0	1 Data Sheet Test NI03 ver2 4P3S2B0	Test result for Pile group 4P3S2B0
NI03 4P3S3B10	2 Data Sheet Test NI03 ver2 4P3S3B10	Test result for Pile group 4P3S3B10
NI03 4P0S3B10	3 Data Sheet Test NI03 ver2 4P0S3B10	Test result for Pile group 4P0S3B10
NI03 4P3S3B0	4 Data Sheet Test NI03 ver2 4P3S3B0	Test result for Pile group 4P3S3B0
NI03 4P0S2B10	5 Data Sheet Test NI03 ver2 4P0S2B10	Test result for Pile group 4P0S2B10
NI03 2P3S2B20	6 Data Sheet Test NI03 ver2 2P3S2B20	Test result for Pile group 2P3S2B20
NI03 4P3S2B10	7 Data Sheet Test NI03 ver2 4P3S2B10	Test result for Pile group 4P3S2B10
NI03 2P3S3B20	8 Data Sheet Test NI03 ver2 2P3S3B20	Test result for Pile group 2P3S3B20

5 Processed Results

The results for individual pile groups are processed in MATHCAD and are presented in details in Appendices C-J.

6 Limitations

The following limitations can be noted from the series of tests:

1. The piles in the pile groups were wished-in-place. Hence, the sand air pluviation was conducted specifying the location of all the piles and pilecaps in the model box.
2. The pile groups were targeted to be tested at 20 g scale units. However, due to the exceedance of the actuator gear motor capacity, the pile groups could not be installed at 20 g but rather installed at 15 g scale units. Moreover, the 20° battered pile groups exceeded the capacity of the actuator even at 15 g scale units; hence, the number of piles were reduced from four to two for two of the pile groups with 20° battered angles.

Limitation on the Gear Motor for Pile Installation: The specified maximum gear motor continuous torque was 16 N-m with a gear head efficiency of 70% that leads to a torque value of 11.2 N-m. Even at 1g, all of the piles reached the maximum capacity at about halfway distance within the pile installation. For example, for the P3 pile, the estimated maximum torque at 1 g (in model scale) was about 20.54 N-m and at 20 g (in prototype scale) was about 164.3 kN-m (Detailed in Appendix K). A larger gear motor than can provide the required torque was again beyond the present accommodation capacity of the centrifuge assembly. In such a case, the feasible solution for pile installation should be the use of a hydraulic gear motor.

Limitation on the Load-Actuator Capacity: The specified maximum load bearing capacity of the actuator was 10 kN at the model scale. Hence, with an operating efficiency at 80% leads to the maximum capacity of 8 kN at the model scale. Hence, when four P3 piles in a group was axially compressed at 20 g scale units the estimated axial capacity per pile was 2.5 (=1000 kN/202) kN in the model scale. Hence for all four piles it stands at 10 kN > 8kN. Analytical calculations at 15 g scale units leads to estimated axial capacity of 1.78 (= 400/152) kN in model scale and for all four its 7.11 kN < 8 kN operational capacity of the actuator, leaving a marginal difference of the operational capacity of only 0.9 kN at the model scale. Hence, later, the pile groups could be successfully compressed at 15 g scale units. Moreover, with the increase in the batter angles of the piles, an increase in the lateral resistance occurred leading to greater bearing zones around the helix locations of the piles. Therefore, for two of the pile groups with 20° battered piles the number of piles had to be reduced from four to two pile groups.

7 Summary

NI03 centrifuge test series consisted of testing eight pile groups in four individual model boxes for ascertain the pile group axial capacity and bending moments on the piles for varied battered angles and spacing. Both smooth and double helix piles were tested in either groups of four or two at the GeoCERF Centrifuge facility at the University of Alberta. The pile groups were pre-installed in dry Sil-3 sand. Appendix C-J presents the results from the centrifuge tests for all the tested model pile groups. The appendices summarize the test results for the axial load capacity and the bending moments over the course of axial displacement of the group and the pile depth. Hence, the internal load transfers along the pile shaft is plotted.

The results presented here are from the third phase of the series of centrifuge tests of helical pile research in the sand at the University of Alberta. The tests were conducted recently and are therefore considered preliminary for the current stage. Detailed interpretation will be presented in the following report or publications.

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Appendix A Schematics and photos of pile group assembly

Appendix B Calibration of strain gauges

Appendix C Data conversion and processing sheet for pile group: 4P3S2B0

Appendix D Data conversion and processing sheet for pile group: 4P3S3B10

Appendix E Data conversion and processing sheet for pile group: 4P0S3B10

Appendix F Data conversion and processing sheet for pile group: 4P3S3B0

Appendix G Data conversion and processing sheet for pile group: 4P0S2B10

Appendix H Data conversion and processing sheet for pile group: 2P3S2B20

Appendix I Data conversion and processing sheet for pile group: 4P3S2B10

Appendix J Data conversion and processing sheet for pile group: 2P3S3B20

Appendix K Analytical Calculations: Ultimate Capacity and Installation Torque

Appendix A

Schematics and Photos of Model Pile caps and Loading Ram

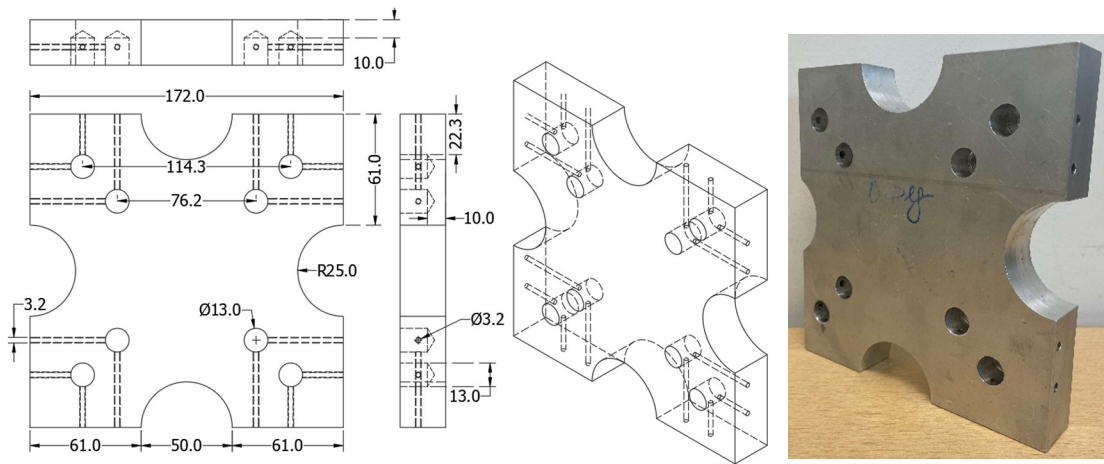


Figure A 1: Schematics and photo of the pile cap for vertical or 0° battered piles.

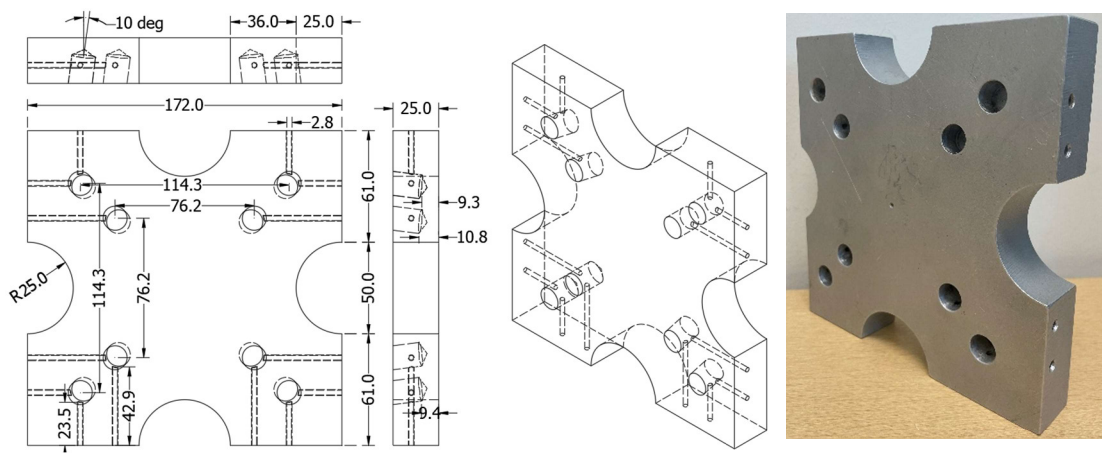


Figure A 2: Schematics and photo of the pile cap for 10° battered piles.

Appendix A

Schematics and Photos of Model Pile caps and Loading Ram

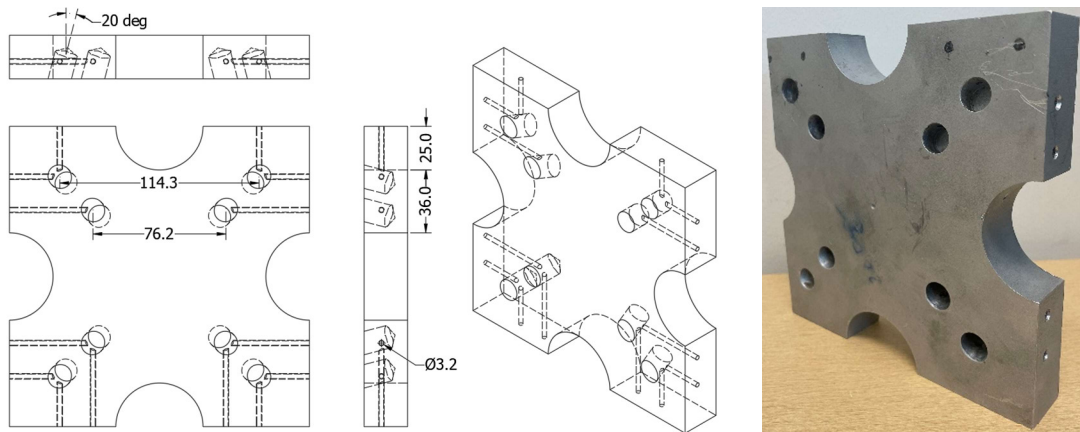


Figure A 3: Schematics and photo of the pile cap for 20° battered piles.

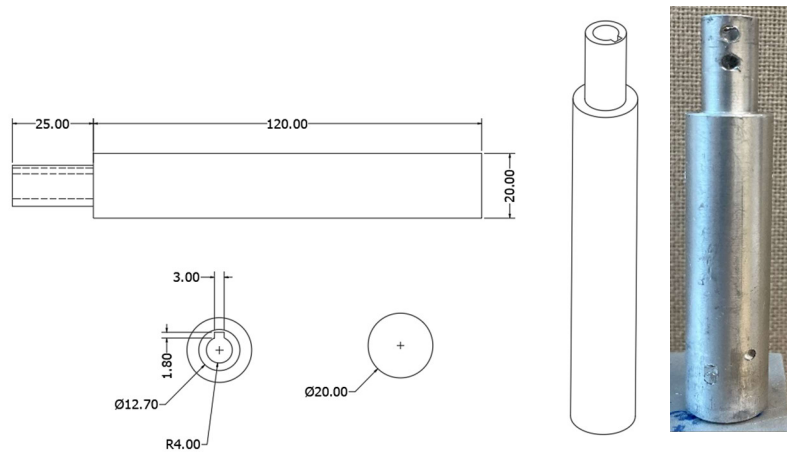


Figure A 4: Schematics and photo of the pile cap loading ram.

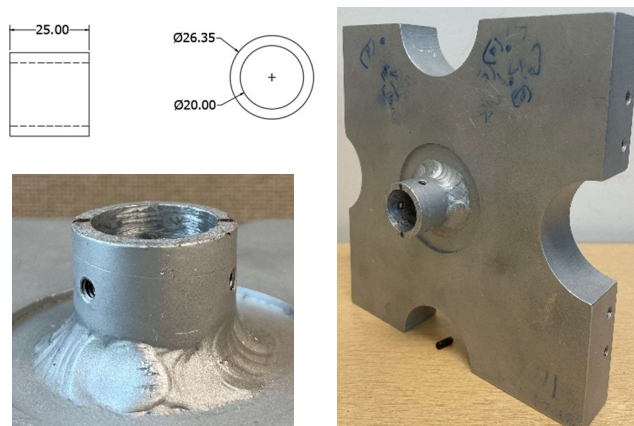


Figure A 5: Schematics and photo of the collar assembly.

Appendix B Calibration of Strain Gauges

1. Calibration of Axial Strain Gauges

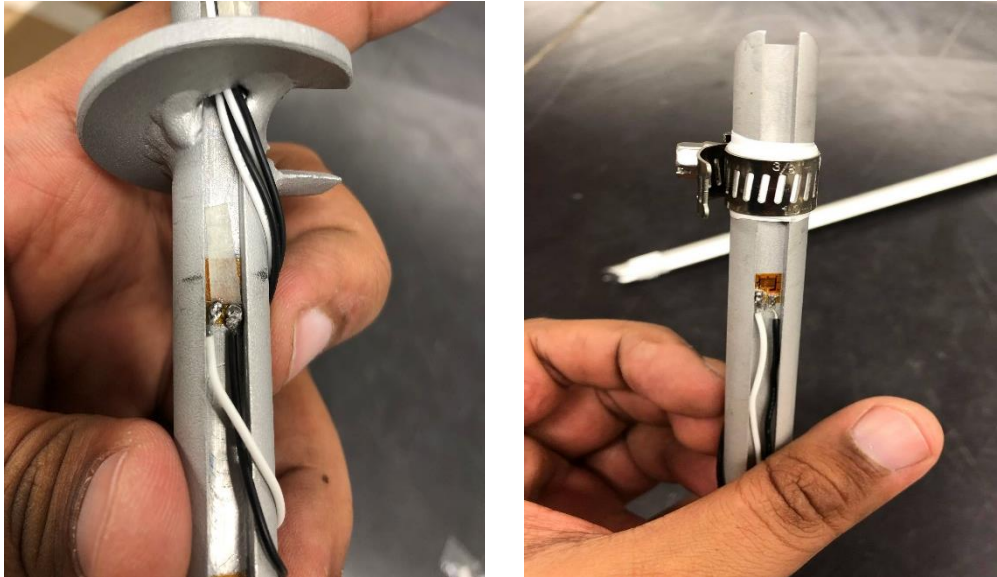
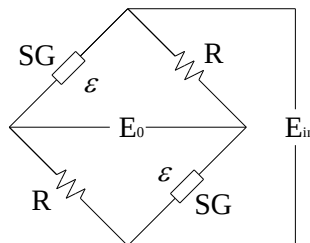


Figure A 1. Installed axial strain gages

The axial strain gauge Half bridge circuit is shown in Figure A2:



a) Axial

Figure A 2. Half bridge circuit for axial strain measurement, where SG = axial strain gauge on pile shaft and R = complementary resistor embedded in the data logger

Analytical Calculations

Young's Modulus of the Aluminum,

$$E_{al} := 70 \cdot \text{GPa}$$

Diameter of the pile head,

Appendix B Calibration of Strain Gauges

$$d_{X_pile} := 12.7 \text{ mm}$$

Cross sectional area of the pile head,

$$A_{X_pile} := \pi \cdot \frac{(d_{X_pile})^2}{4} = 126.677 \text{ mm}^2$$

Groove width,

$$b := 5 \text{ mm}$$

Groove depth,

$$h := 3.27 \text{ mm}$$

Arc angle,

$$\theta := 2 \cdot \arccos \left(\frac{\frac{b}{2}}{\frac{d_{X_pile}}{2}} \right) \cdot \frac{180}{\pi} = 133.63$$

Cross sectional area at the strain gage location,

$$A_{SG_pile} := 2 \cdot \frac{1}{2} \cdot \left(\frac{d_{X_pile}}{2} \right)^2 \cdot \left(\left(\frac{\pi}{180} \cdot \theta \right) - \sin \left(\theta \cdot \frac{\pi}{180} \right) \right) + \left(2 \cdot \sqrt{\left(\left(\frac{d_{X_pile}}{2} \right)^2 - \left(\frac{b}{2} \right)^2} \right) - (2 \cdot h)} \right) \cdot b = 90.529 \text{ mm}^2$$

Poisson's ratio,

$$\nu := 0.3$$

Shear Modulus of the Aluminum,

$$G_{al} := \frac{E_{al}}{2(1+\nu)} = 26.923 \text{ GPa}$$

Outer diameter of the adaptor,

$$d_{adap_out} := d_{X_pile} + 1.5875 \text{ mm} = 14.288 \text{ mm}$$

Inner diameter of the adaptor,

$$d_{adap_in} := d_{X_pile} = 12.7 \text{ mm}$$

Polar moment of inertia of the adaptor,

Appendix B Calibration of Strain Gauges

$$J_{adaptor} := \pi \cdot \frac{\left(\left(\frac{d_{adap_out}}{2} \right)^4 - \left(\frac{d_{adap_in}}{2} \right)^4 \right)}{2} = (1.537 \cdot 10^3) \text{ mm}^4$$

Output signal factor,

$$a := 200$$

Output voltage,

$$E_0 := 1 \cdot \text{mV}$$

Input voltage,

$$E_{in} := 1 \cdot \text{V}$$

Axial Gage Factor,

$$GF_{axial} := 2.14 \quad \leftarrow \text{Manufacturer}$$

Axial Strain,

$$\varepsilon_a := 2 \cdot a \cdot \frac{E_0}{E_{in} \cdot GF_{axial}} = 0.187$$

Axial Force,

$$F := E_{al} \cdot A_{SG_pile} \cdot \varepsilon_a = 1184.5 \text{ kN}$$

The theoretical axial force per 1mV/V of HBM output are estimated.

Adopted Load Combinations

$$F_1 := 43.43 \text{ N} \quad \varepsilon_1 := \frac{F_1}{E_{al} \cdot A_{SG_pile}} = 6.853 \frac{1}{\text{m}} \cdot \mu\text{m}$$

$$F_2 := 78.18 \text{ N} \quad \varepsilon_2 := \frac{F_2}{E_{al} \cdot A_{SG_pile}} = 12.337 \frac{1}{\text{m}} \cdot \mu\text{m}$$

$$F_3 := 133.51 \text{ N} \quad \varepsilon_3 := \frac{F_3}{E_{al} \cdot A_{SG_pile}} = 21.068 \frac{1}{\text{m}} \cdot \mu\text{m}$$

Appendix B

Calibration of Strain Gauges

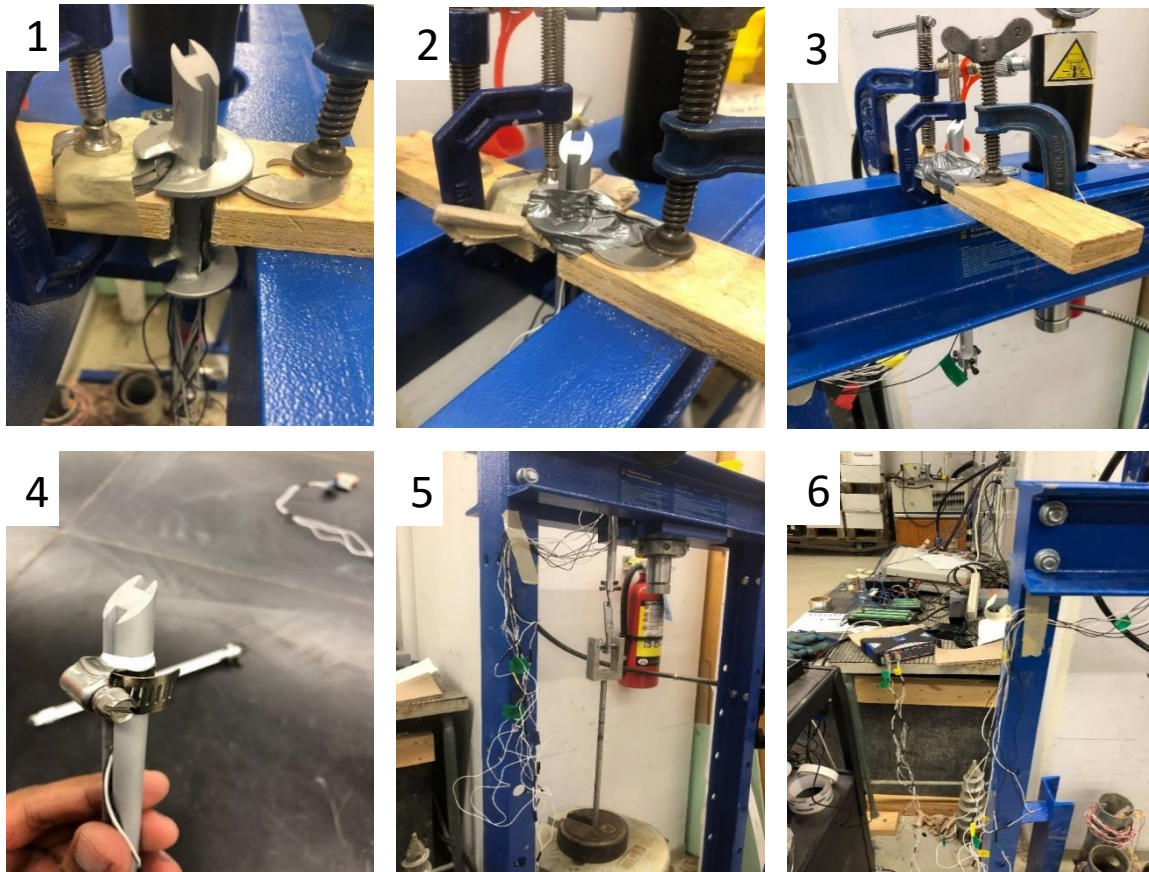


Figure A 3. Axial strain gauge calibration setup

Appendix B

Calibration of Strain Gauges

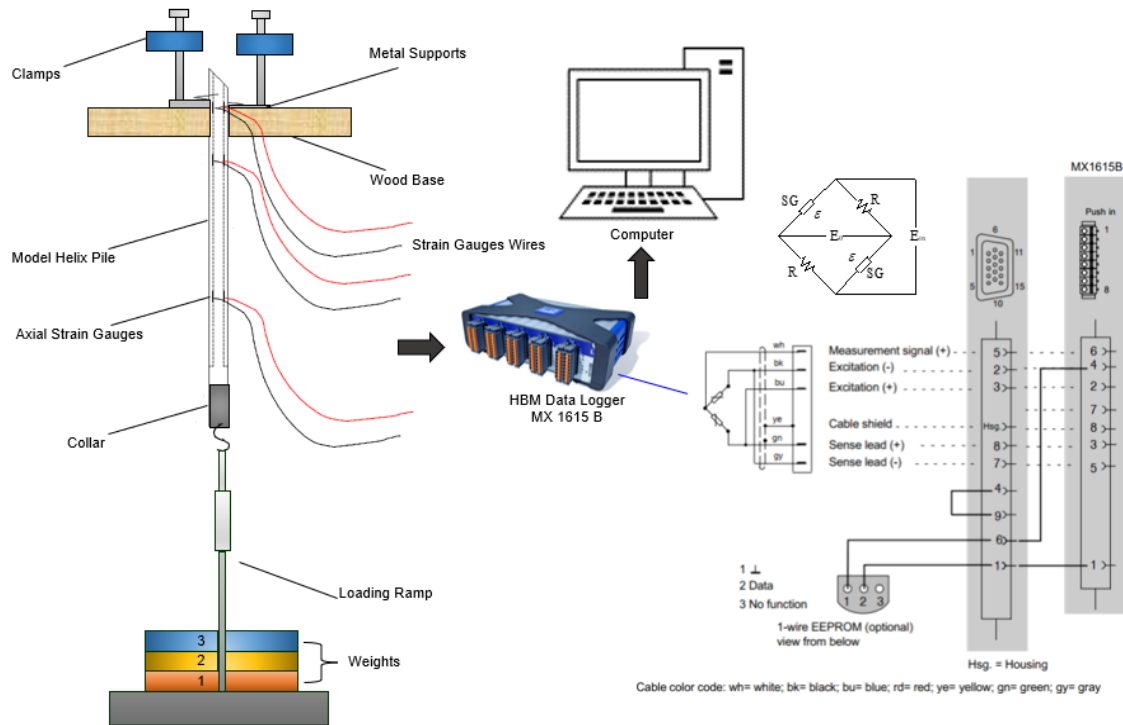


Figure A 4. Schematic calibration of axial strain gauges.

Table A 1. Calibration measurements for Axial Strain Gauges from the HBM Data Logger

Pile	Applied Load (N)	HBM Strain ($\mu\text{m/m}$)	HBM readings 10-3 (mV/V)	K_a (kN/mV/V)
P1	43.43	7.30	0.037	1190
	78.18	12.53	0.063	1248
	133.51	23.23	0.116	1149
P2	43.43	6.83	0.034	1273
	78.18	12.30	0.062	1271
	133.51	22.05	0.110	1211
P3	43.43	7.28	0.036	1194
	78.18	12.23	0.061	1278
	133.51	23.16	0.116	1153
P4	43.43	7.33	0.037	1186
	78.18	12.64	0.063	1237
	133.51	21.14	0.106	1263

Appendix B

Calibration of Strain Gauges

Pile	Applied Load (N)	HBM Strain ($\mu\text{m/m}$)	HBM readings 10-3 (mV/V)	K_a (kN/mV/V)
P0	43.43	6.97	0.035	1246
	78.18	12.60	0.063	1241
	133.51	23.36	0.117	1143
Average K_a (kN/mV/V)				1219

Table A 2. Summary of the axial strain gauge calibration results

SG type	Gauge Factor	Bridge type	Rosette	Excitation (V)	Calibration factor
Axial	2.14	Half	Axial	10	1219 kN/(mV/V)

Appendix B Calibration of Strain Gauges

2. Calibration of Bending Strain Gauges



Figure A 5. Installed bending strain gauges.

Analytical Calculations

Calculation of Section Modulus

$$r := 3.85 \text{ mm} \quad b := 7.85 \text{ mm} \quad h := 5 \text{ mm} \quad c_{xx} := \frac{h}{2} \quad c_{yy} := \frac{b}{2} + r$$

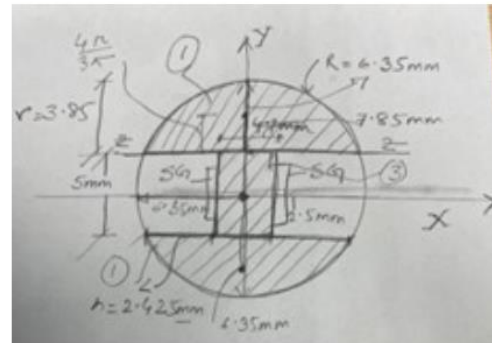
$$x_1 := 0 \text{ mm} \quad x_2 := 0 \text{ mm} \quad x_3 := 0 \text{ mm}$$

$$y_1 := \frac{4 \cdot r}{3 \pi} + \frac{h}{2} \quad y_2 := \frac{4 \cdot r}{3 \pi} + \frac{h}{2} \quad y_3 := 0 \text{ mm}$$

$$A_1 := \pi \cdot r^2 \quad A_2 := \pi \cdot r^2 \quad A_3 := b \cdot h$$

$$x_c := \frac{(A_1 \cdot x_1) + (A_2 \cdot x_2) + (A_3 \cdot x_3)}{(A_1 + A_2 + A_3)} = 0 \text{ mm}$$

$$y_c := \frac{(A_1 \cdot y_1) + (A_2 \cdot y_2) + (A_3 \cdot y_3)}{(A_1 + A_2 + A_3)} = 2.908 \text{ mm}$$



Appendix B

Calibration of Strain Gauges

MOI wrt Centroidal X-X

$$I_{G1} := 0.11 \cdot r^4 = 24.168 \text{ mm}^4$$

$$I_{G2} := 0.11 \cdot r^4 = 24.168 \text{ mm}^4$$

$$I_{G3} := b \cdot \frac{h^3}{12} = 81.771 \text{ mm}^4$$

$$I_{xx1} := I_{G1} + \left(A_1 \cdot (y_1 - y_c)^2 \right) = (9.412 \cdot 10^{-11}) \text{ m}^4$$

$$I_{xx2} := I_{G2} + \left(A_2 \cdot (y_2 - y_c)^2 \right) = (9.412 \cdot 10^{-11}) \text{ m}^4$$

$$I_{xx3} := I_{G3} + \left(A_3 \cdot (y_3 - y_c)^2 \right) = 413.757 \text{ mm}^4$$

$$I_{xx} := I_{xx1} + I_{xx2} + I_{xx3} = 602.006 \text{ mm}^4$$

$$S_{xx} := \frac{I_{xx}}{c_{yy}} = 77.428 \text{ mm}^3$$

MOI wrt Centroidal Y-Y

$$I_{G1} := 0.393 \cdot r^4 = 86.345 \text{ mm}^4$$

$$I_{G2} := 0.393 \cdot r^4 = 86.345 \text{ mm}^4$$

$$I_{G3} := h \cdot \frac{b^3}{12} = 201.557 \text{ mm}^4$$

$$I_{yy1} := I_{G1} + \left(A_1 \cdot (x_1 - x_c)^2 \right) = (8.634 \cdot 10^{-11}) \text{ m}^4$$

$$I_{yy2} := I_{G2} + \left(A_2 \cdot (x_2 - x_c)^2 \right) = (8.634 \cdot 10^{-11}) \text{ m}^4$$

$$I_{yy3} := I_{G3} + \left(A_3 \cdot (x_3 - x_c)^2 \right) = 201.557 \text{ mm}^4$$

$$I_{yy} := I_{yy1} + I_{yy2} + I_{yy3} = 374.246 \text{ mm}^4$$

$$S_{yy} := \frac{I_{yy}}{c_{xx}} = 149.698 \text{ mm}^3 \quad \leq \text{Use in design}$$

Theoretical Bending Moment:

Young's Modulus of the Aluminum, $E_{al} := 70 \cdot \text{GPa}$

Yield Stress of Aluminum $\sigma_y := 240 \text{ MPa}$

Diameter of the pile head, $d_{X_pile} := 12.7 \text{ mm}$

Cross sectional area of the pile head, $A_{X_pile} := \pi \cdot \frac{(d_{X_pile})^2}{4} = 126.677 \text{ mm}^2$

Groove width, $b := 5 \text{ mm}$ Groove depth, $h := 2.425 \text{ mm}$

Appendix B

Calibration of Strain Gauges

$$\text{Arc angle, } \theta := 2 \cdot \arccos \left(\frac{\frac{b}{2}}{\frac{d_{X_pile}}{2}} \right) \cdot \frac{180}{\pi} = 133.63$$

Cross sectional area at the strain gage location,

$$A_{SG_pile} := 2 \cdot \frac{1}{2} \cdot \left(\frac{d_{X_pile}}{2} \right)^2 \cdot \left(\left(\frac{\pi}{180} \cdot \theta \right) - \sin \left(\theta \cdot \frac{\pi}{180} \right) \right) + \left(2 \cdot \sqrt{\left(\left(\frac{d_{X_pile}}{2} \right)^2 - \left(\frac{b}{2} \right)^2} \right) - (2 \cdot h)} \right) \cdot b = 98.979 \text{ mm}^2$$

Poisson's ratio,

$$\nu := 0.3$$

Shear Modulus of the Aluminum,

$$G_{al} := \frac{E_{al}}{2(1+\nu)} = 26.923 \text{ GPa}$$

Outer diameter of the adaptor,

$$d_{adap_out} := d_{X_pile} + 1.5875 \text{ mm} = 14.288 \text{ mm}$$

Inner diameter of the adaptor,

$$d_{adap_in} := d_{X_pile} = 12.7 \text{ mm}$$

Elastic Section Modulus,

$$S_M := 149.698 \text{ mm}^3$$

$$S_Y := 77.428 \text{ mm}^3$$

Polar moment of inertia of the adaptor,

$$J_{adaptor} := \pi \cdot \frac{\left(\left(\frac{d_{adap_out}}{2} \right)^4 \right)}{2} = (4.091 \cdot 10^3) \text{ mm}^4$$

Output signal factor,

$$a := 200$$

Output voltage,

$$E_0 := 1 \cdot \text{mV}$$

Input voltage,

$$E_{in} := 1 \cdot \text{V}$$

Bending Gage Factor,

$$GF_{bending} := 2.11$$

<= Manufacturer (NEW)

Bending Strain,

$$\varepsilon_b := 2 \cdot a \cdot \frac{E_0}{E_{in} \cdot GF_{bending}} = 0.19$$

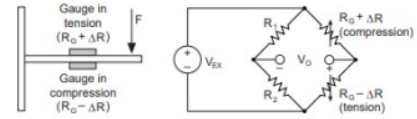
Bending Stress,

$$\sigma_b := E_{al} \cdot \varepsilon_b = 13270.1 \text{ MPa}$$

Bending Moment,

$$M_{b_max} := \sigma_b \cdot S_M = 1.987 \text{ (kN} \cdot \text{m)}$$

$$M_{b_min} := \sigma_b \cdot S_Y = 1.027 \text{ kN} \cdot \text{m}$$



$$\frac{V_O}{V_{EX}} = \frac{GF \cdot \varepsilon}{2}$$

Figure 6. Half-Bridge Circuit

Appendix B

Calibration of Strain Gauges



Figure A 6. Bending strain gauge calibration setup

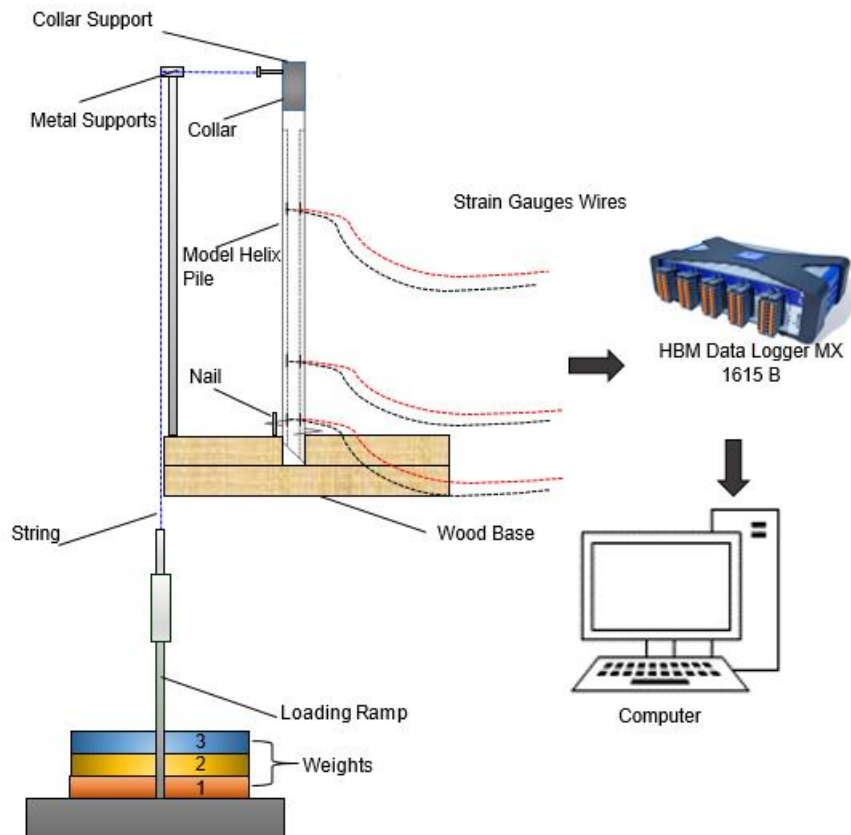


Figure A 7. Schematic of calibration setup for bending strain gauges.

Appendix B

Calibration of Strain Gauges

Table A 3. Calibration measurements for bending strain gauges from the HBM Data Logger

Loads (kg)	Distance to SG (mm)	SG	HBM readings (mV/V)						K _t (kN-m/mV/V)						
			P0B1	P0B2	P3B1	P3B2	P3B3	P3B4	P0B1	P0B2	P3B1	P3B2	P3B3	P3B4	Avg
2.40	212	1	0.003	0.003	0.003	0.002	0.002	0.002	1.67	1.62	1.84	2.16	2.04	2.13	1.91
4.41	212	1	0.006	0.005	0.005	0.005	0.006	0.004	1.60	1.91	2.02	1.89	1.66	2.11	1.87
9.36	212	1	0.013	0.012	0.013	0.011	0.016	0.010	1.51	1.57	1.54	1.76	1.21	1.88	1.58
2.40	147	2	0.000	0.000	0.002	0.002	0.002	0.002	N A	N A	1.80	1.57	1.86	2.11	1.84
4.41	147	2	0.000	0.000	0.003	0.004	0.004	0.003	N A	N A	1.95	1.54	1.64	2.10	1.81
9.36	147	2	0.000	0.000	0.009	0.009	0.009	0.007	N A	N A	1.58	1.52	1.50	1.96	1.64
2.40	120	3	0.000	0.000	0.002	0.002	0.002	0.001	N A	N A	1.85	1.65	1.74	2.08	1.83
4.41	120	3	0.000	0.000	0.003	0.003	0.004	0.002	N A	N A	1.99	1.58	1.48	2.14	1.79
9.36	120	3	0.000	0.000	0.007	0.007	0.008	0.005	N A	N A	1.62	1.56	1.46	2.03	1.67
2.40	85	4	0.001	0.001	0.001	0.001	0.001	0.001	2.33	1.81	2.13	1.66	1.70	2.23	1.98
4.41	85	4	0.002	0.002	0.002	0.002	0.002	0.002	1.79	1.80	2.13	1.71	1.75	2.33	1.92
9.36	85	4	0.004	0.005	0.005	0.005	0.004	0.003	1.89	1.67	1.71	1.66	1.81	2.44	1.86

1.808

Table A 4. Summary of the bending strain gauge calibration results

SG type	Gauge Factor	Bridge type	Rosette	Excitation (V)	Calibration factor
Bending	2.11	Half	Diagonal	10	1.808 kN-m/(mV/V)

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

1. Introduction

The series of sheets in Appendix C contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P3S2B0 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

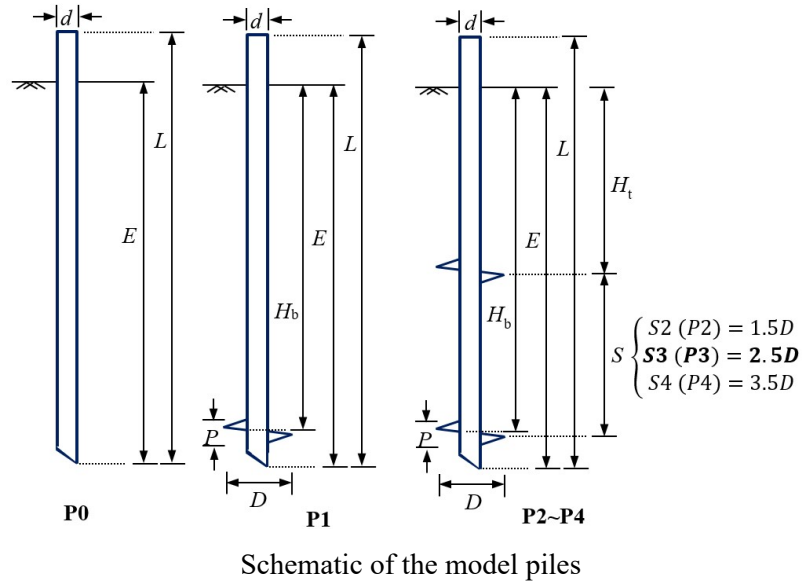
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P3= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \frac{kN \cdot m}{mV} \frac{mV}{V}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \begin{aligned} & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \cdot \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \cdot \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \quad \quad \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & \text{SG1}_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG2}_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG3}_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG4}_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \end{aligned} \\ & \text{augment}(\text{medsmooth}(\text{SG1}^{(0)}, \text{smthn}), \text{medsmooth}(\text{SG2}^{(1)}, \text{smthn}), \text{medsmooth}(\text{SG3}^{(2)}, \text{smthn}), \text{medsmooth}(\text{SG4}^{(3)}, \text{smthn})) \end{aligned}
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{aligned} & \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \\ & \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ & \quad \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow -(\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ & \text{augment}(k, q) \end{aligned}
 \end{aligned}$$

Appendix C

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$G4P3S2B0HBM := \text{READExcel}(\text{".\2P3B0G.xlsx"}, \text{"Sheet1 (2)!A3:M9073"})$

$\text{TimeDispG4P3S2B0} := \text{TimeZero}(G4P3S2B0HBM)$

$\text{AxLdG4P3S2B0} := \text{ConvLd}(G4P3S2B0HBM, 3, \text{CFAxl}, 111, 1)$

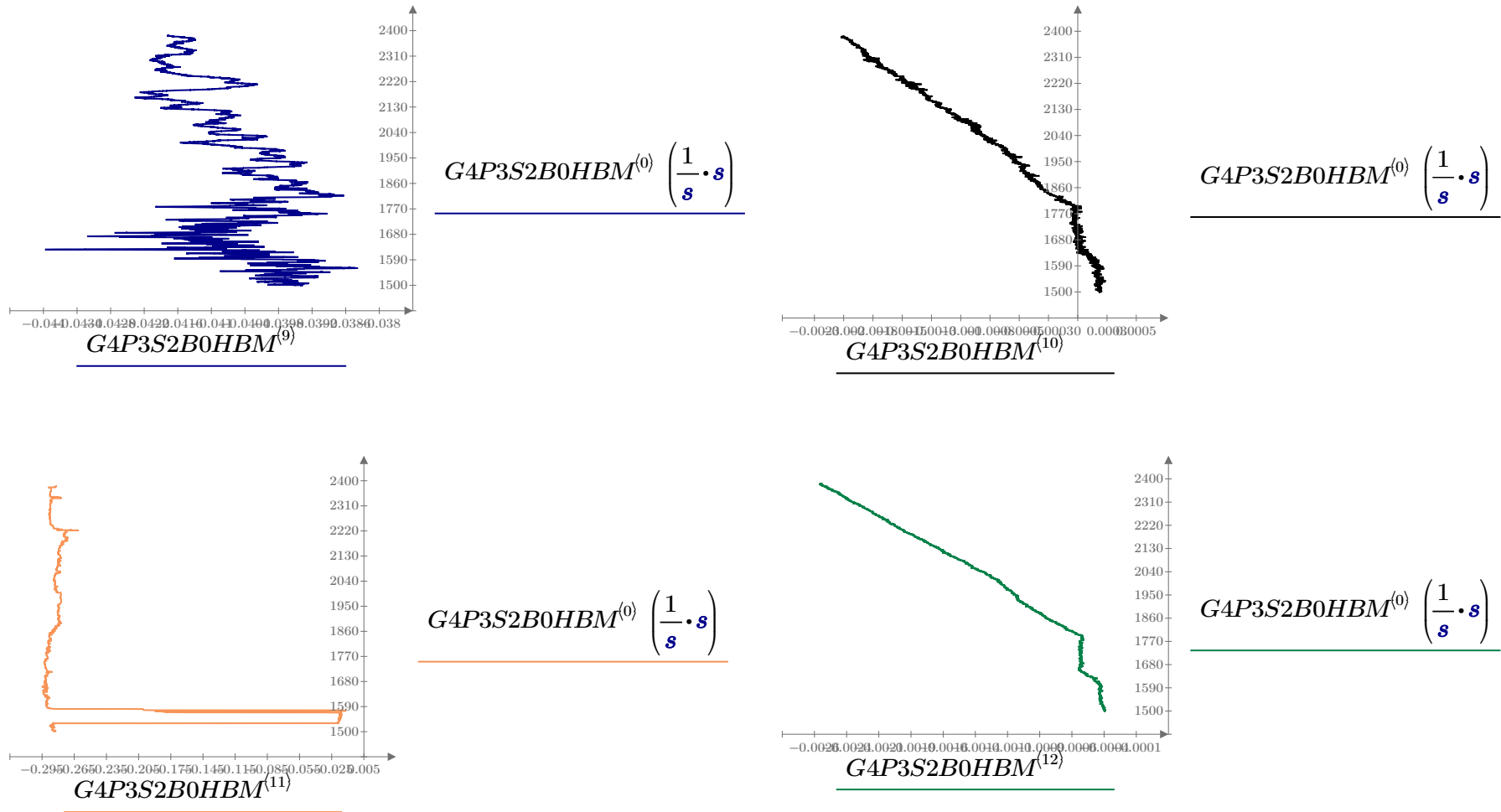


Fig C 1. Rawdata axial load time history for pile group 4P3S2B0

Appendix C
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

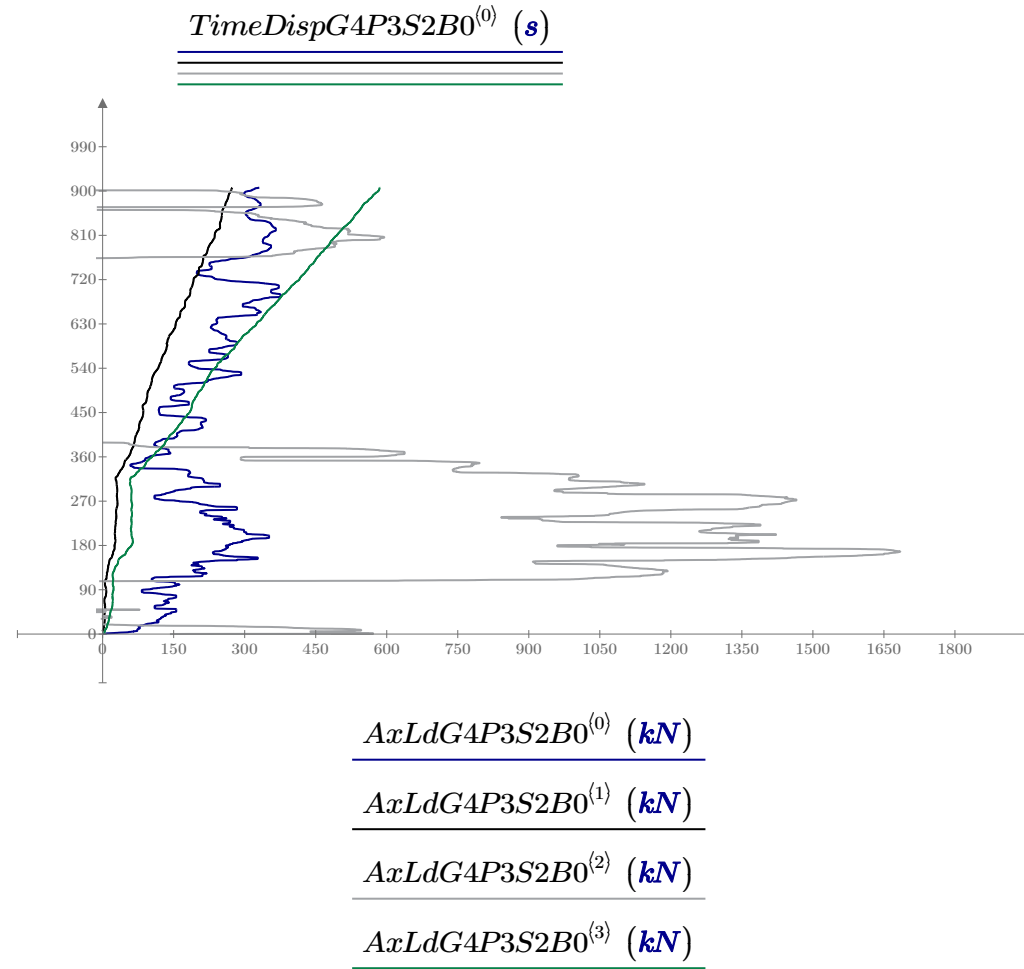


Fig C 2. Axial Load time history for pile group 4P3S2B0

Appendix C
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

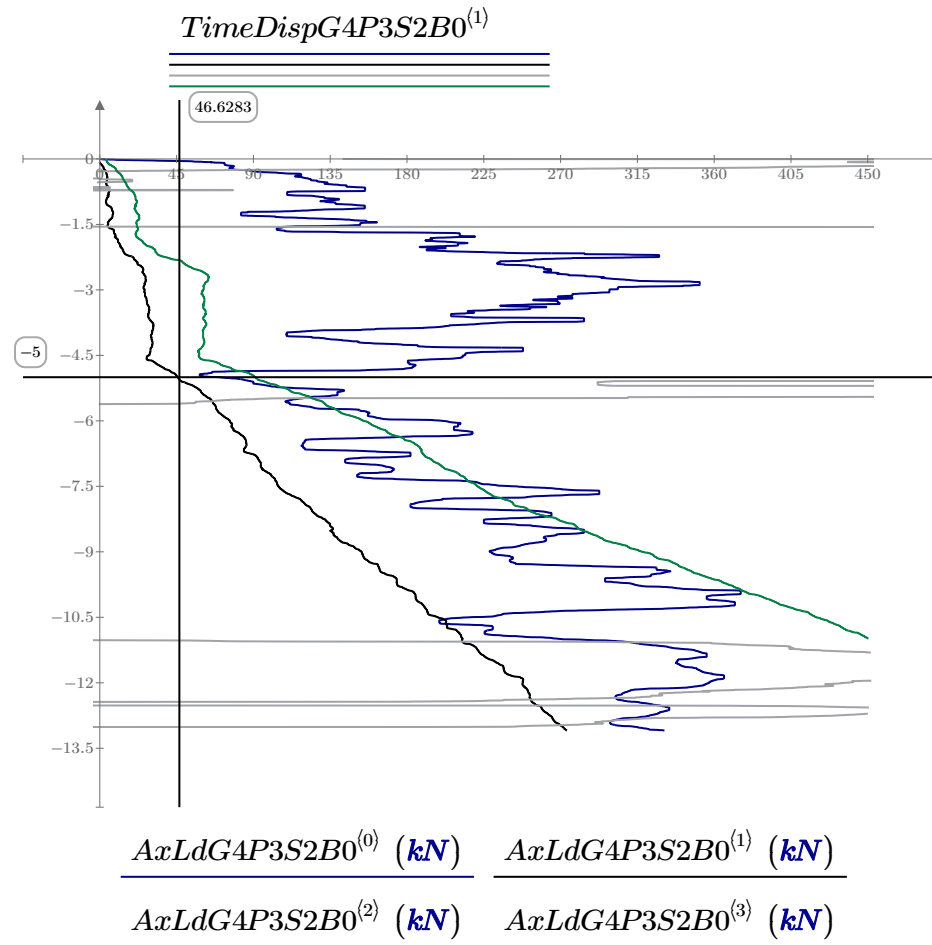


Fig C 3. Axial Load -displacement for pile group 4P3S2B0

Appendix C

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SCplotQP (AzLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
  ||
  || augment (lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near"))
  ||
  || else
  ||
  || augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near"))
  ||
  QP1 ← if PileNum = 0
  ||
  || augment (lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near"))
  ||
  || else
  ||
  || augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(1) , "near"))
  ||
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near"))
  ||
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near"))
  ||
  combined ← if PileNum = 0
  ||
  || stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  ||
  || else
  ||
  || stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  ||
  combined

```

$$Qdist4P3S2B0 := SGplotQP (AzLdG4P3S2B0 , TimeDispG4P3S2B0 , 3) = \begin{bmatrix} 260.2702 & 70.4429 & 243.2962 & 358.4373 \\ 25.244 & 45.688 & 104.887 & 185.0633 \\ 25.244 & 45.688 & 104.887 & 185.0633 \\ 1559.2755 & 790.7165 & -1535.984 & -1445.9148 \\ 1559.2755 & 790.7165 & -1535.984 & -1445.9148 \\ 54.1873 & 91.1842 & 221.2338 & 386.038 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{selfac_{0,0}}$$

SG embedment depth in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 5 represents depth to strain SG 1 to 4

Appendix C
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

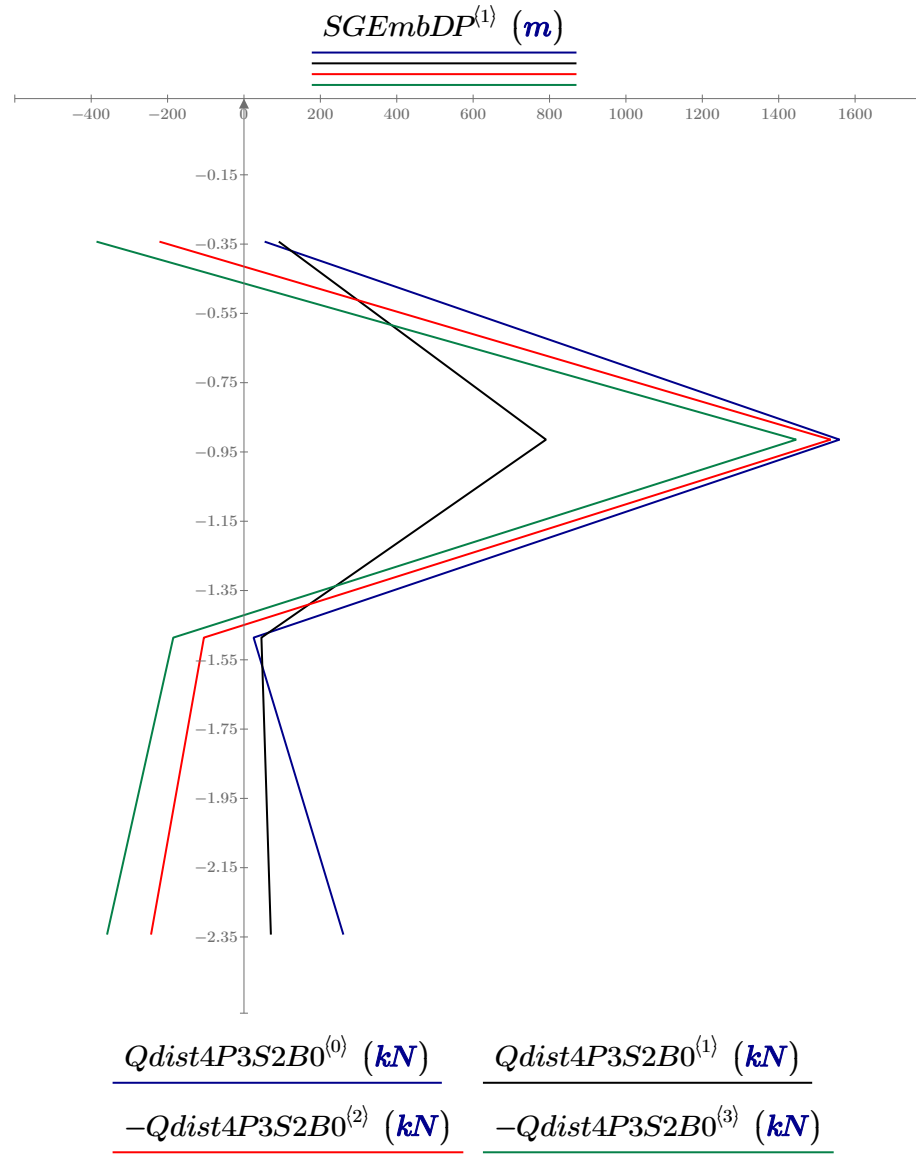


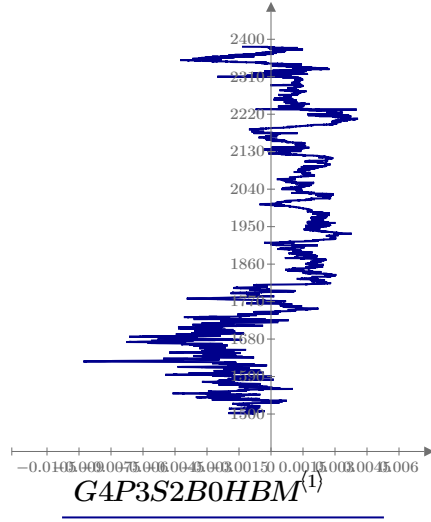
Fig C 4. Axial Load distribution with depth for pile group 4P3S2B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

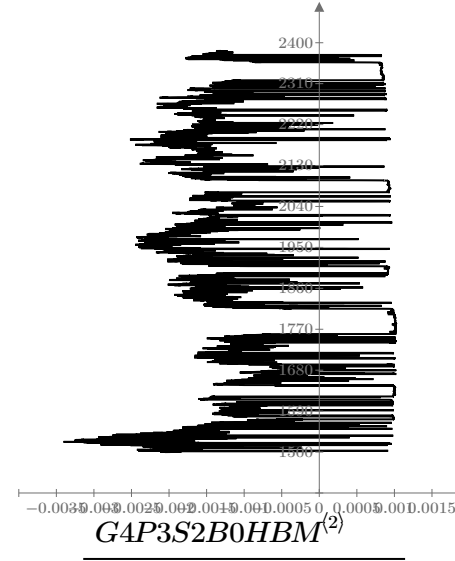
2.3.3 Bending Moment vs Time

$BM1_{G4P3S2B0} := ConvLd(G4P3S2B0HBM, 4, CFBM, 111, 2)$

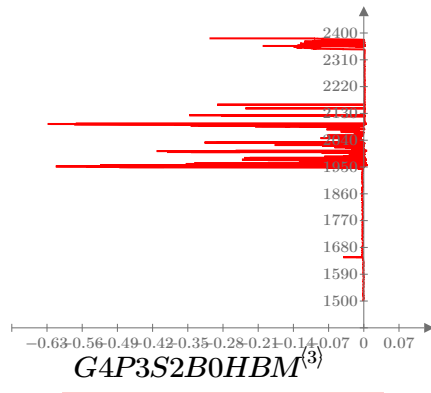
$BM2_{G4P3S2B0} := ConvLd(G4P3S2B0HBM, 2, CFBM, 77, 3)$



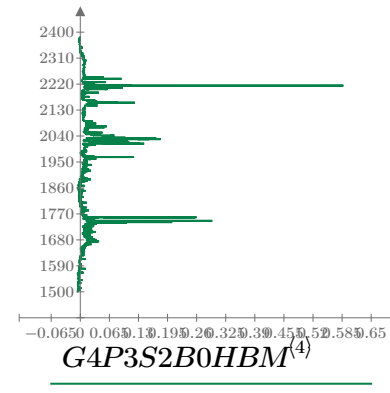
$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



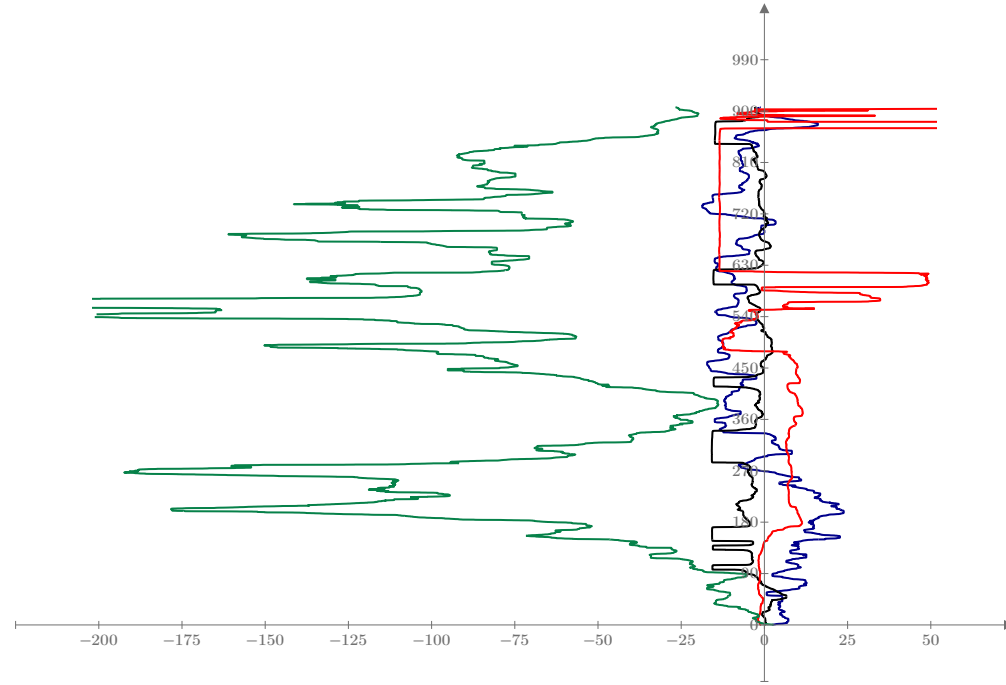
$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$

Fig C 5. Raw Data Bending Moment 1 for pile group 4P3S2B0

$$\underline{\underline{TimeZero(G4P3S2B0HBM)^{(0)}} \text{ (s)}}$$



$$\underline{\underline{BM1G4P3S2B0^{(0)}} \text{ (m} \cdot \text{kN)}}$$

$$\underline{\underline{BM1G4P3S2B0^{(1)}} \text{ (m} \cdot \text{kN)}}$$

$$\underline{\underline{BM1G4P3S2B0^{(2)}} \text{ (m} \cdot \text{kN)}}$$

$$\underline{\underline{BM1G4P3S2B0^{(3)}} \text{ (m} \cdot \text{kN)}}$$

Fig C 6. Bending Moment 1 time history for pile group 4P3S2B0

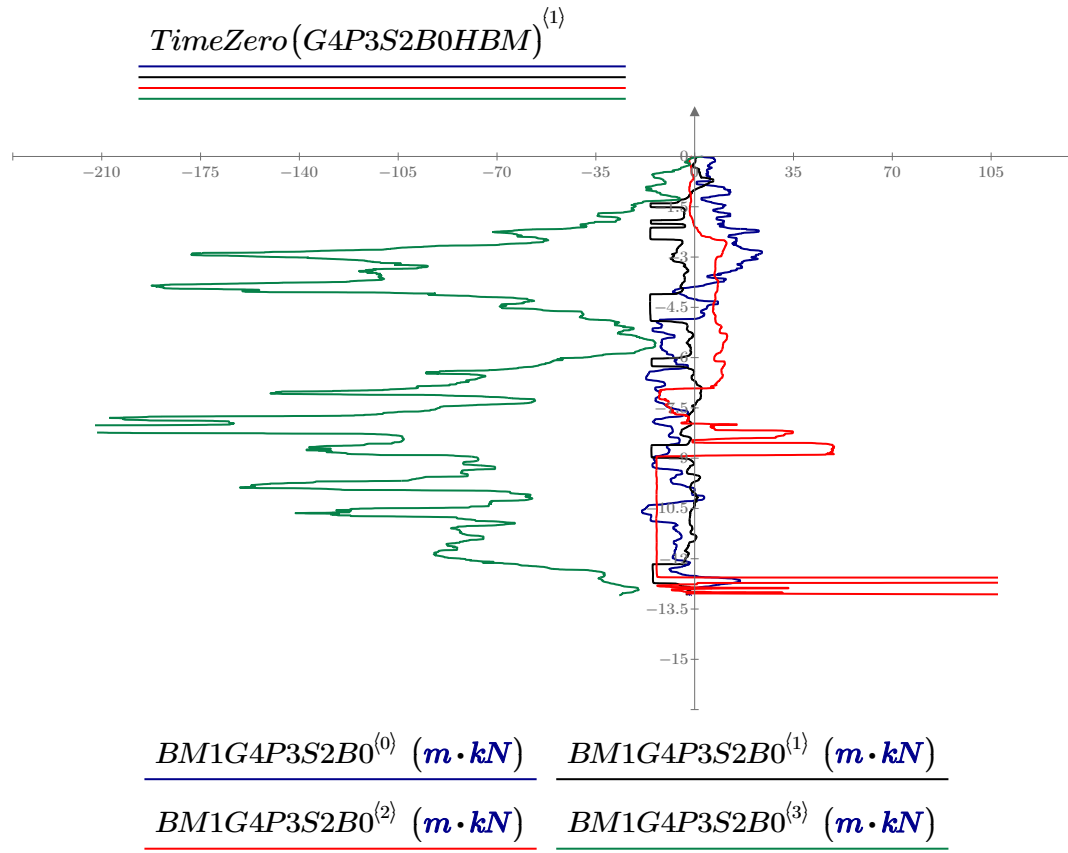


Fig C 7. Bending Moment 1 - displacement for pile group 4P3S2B0

$$BMM_{axdist4P3S2B0} := SGplotQP(BM1G4P3S2B0, TimeDispG4P3S2B0, 3) = \begin{bmatrix} 14.8869 & -11.8744 & -8.336 & -0.3507 \\ -4.8297 & -2.7679 & -0.0731 & -0.8279 \\ -4.8297 & -2.7679 & -0.0731 & -0.8279 \\ 10.466 & 8.1318 & -8.9048 & -13.4975 \\ 10.466 & 8.1318 & -8.9048 & -13.4975 \\ -51.8354 & -27.5261 & -90.4794 & -66.3408 \end{bmatrix} m \cdot kN$$

Appendix C
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

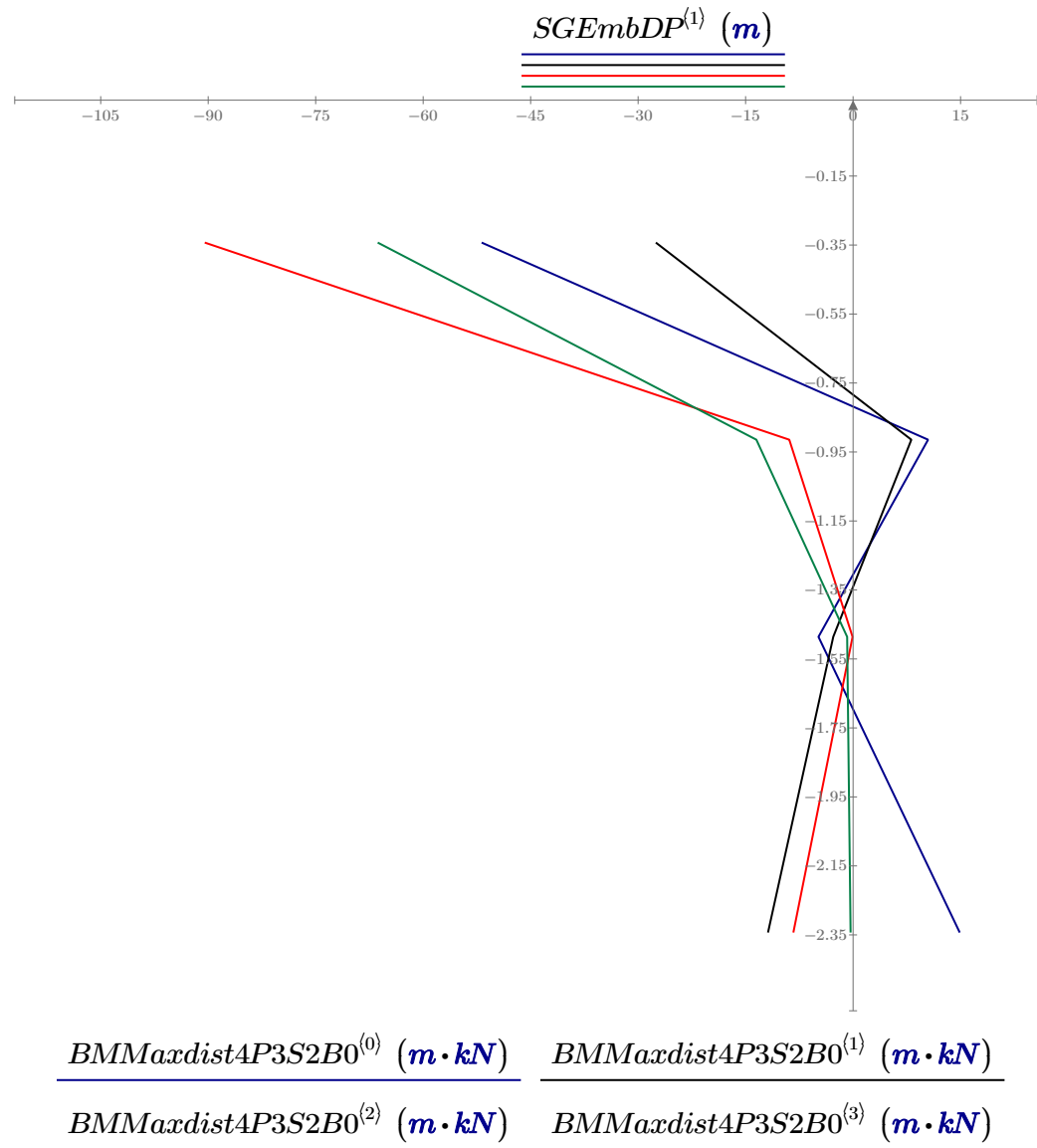
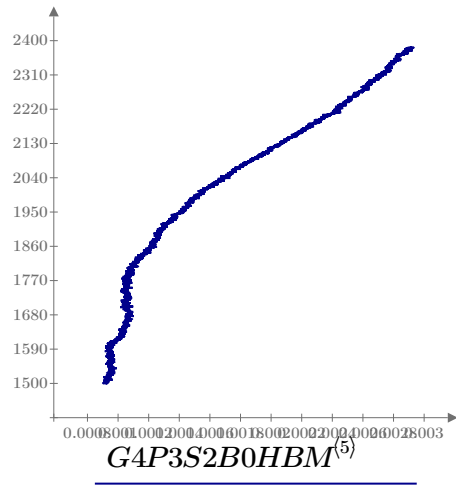
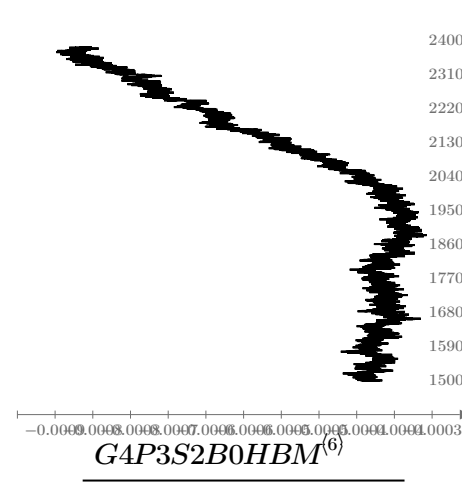


Fig C 8. Bending Moment 1 - depth for pile group 4P3S2B0

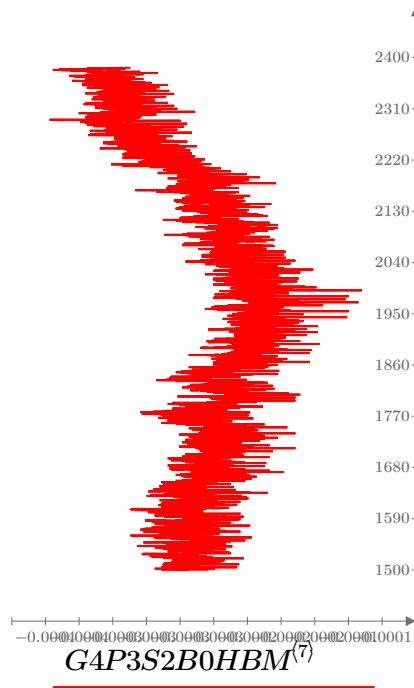
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group



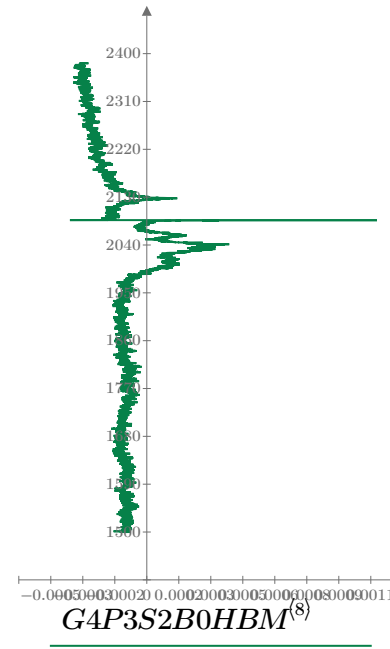
$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S2B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$

Fig C 9. Raw Data Bending Moment 2 for pile group 4P3S2B0

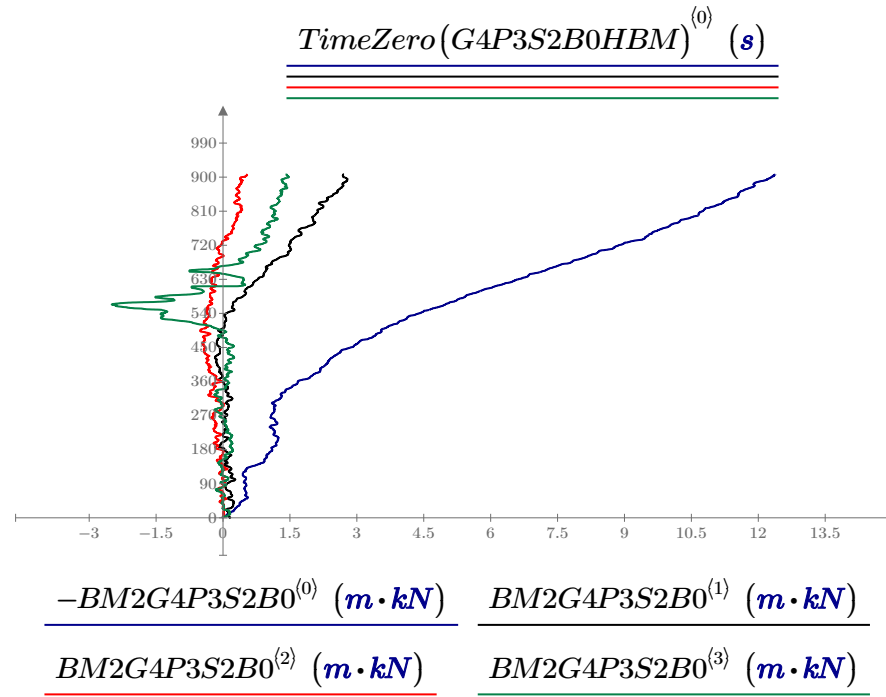


Fig C 10. Bending Moment 2 time history for pile group 4P3S2B0

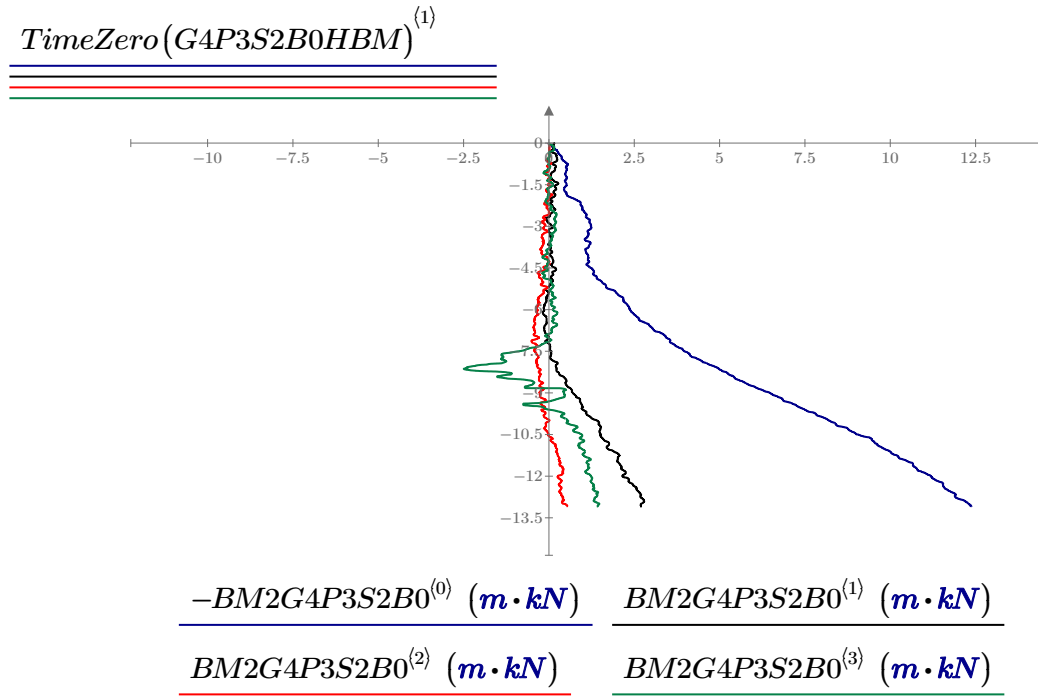


Fig C 11. Bending Moment 2 - displacement for pile group 4P3S2B0

$$BMMindist4P3S2B0 := SGplotQP(BM2G4P3S2B0, TimeDispG4P3S2B0, 3) = \begin{bmatrix} -1.0431 & -1.5516 & -3.9622 & -8.2049 \\ 0.0949 & 0.0949 & 0.0431 & 1.4149 \\ 0.0949 & 0.0949 & 0.0431 & 1.4149 \\ 0 & -0.1682 & -0.425 & 0.0177 \\ 0 & -0.1682 & -0.425 & 0.0177 \\ 0.145 & 0.058 & -0.8702 & 0.5511 \end{bmatrix} m \cdot kN$$

Appendix C
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

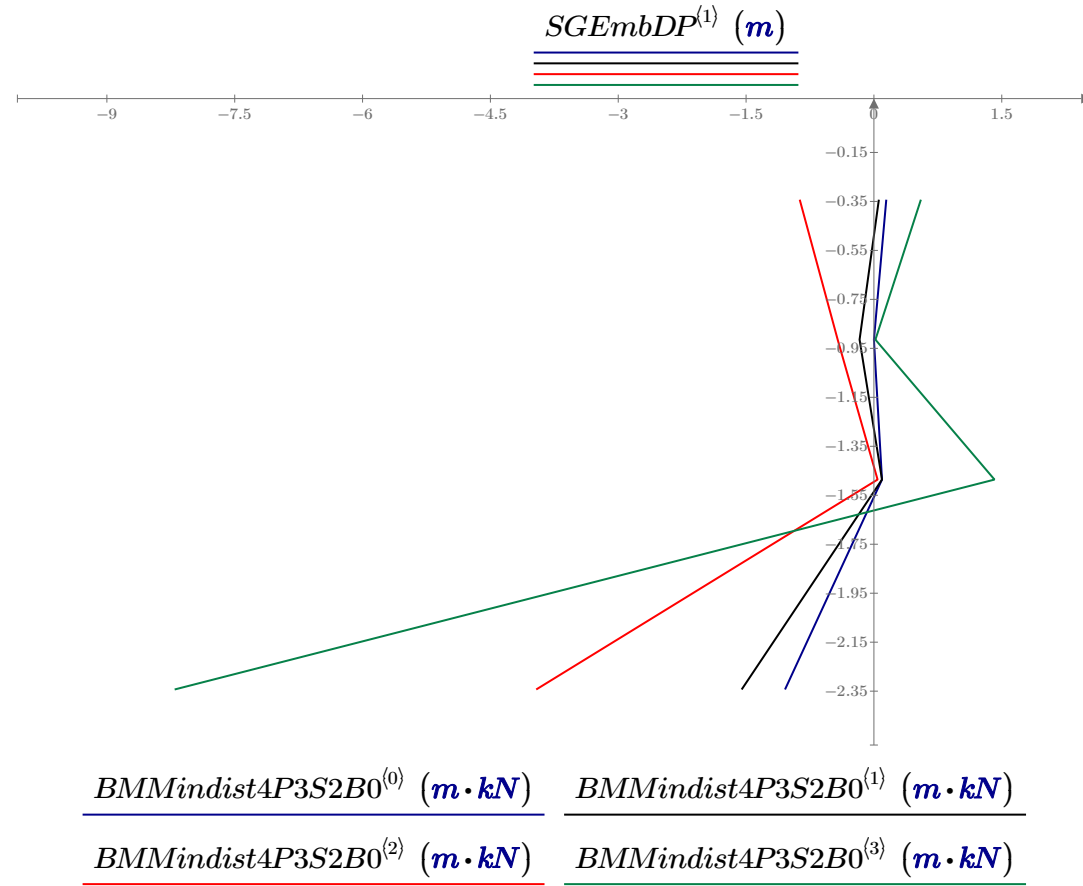


Fig C 12. Bending Moment 2 - depth for pile group 4P3S2B0

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) := || TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
    LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
    LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
    for i ∈ 0, 1..rows(LVDTRawData) - 1
        || k_i ← (TimeLVDT_i - TimeLVDT_0)
        || q_i ← -(LVDT1_i - LVDT1_0) · 2 · Nscalescifac0,0
        || m_i ← -(LVDT2_i - LVDT2_0) · 2 · Nscalescifac0,0
        || n_i ← -(TimeLVDT_i - TimeLVDT_0) · CmpRate · Nscalescifac0,0
    || augment(k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-2P3B0G.xlsx"}, \text{"Sheet3 (2)!A2:C954"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

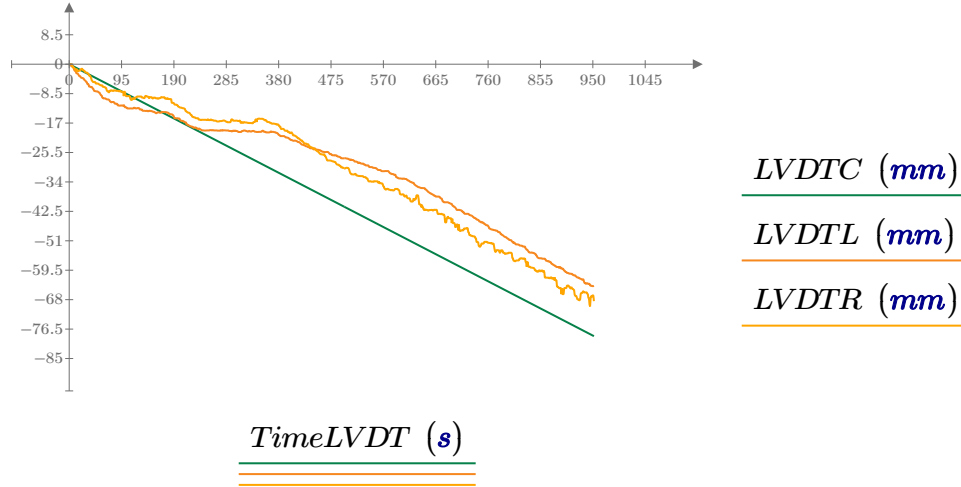


Fig C 13. LVDT displacements time history for pile group 4PS2B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B0 Helix Pile Group

Function for determining the tilting of the plate

$$Tilt(SpacingDCDLR, SpacingDLDR) := \begin{cases} k \leftarrow (SpacingDCDLR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ q \leftarrow (SpacingDLDR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ \text{for } i \in 0, 1 \dots \text{rows}(LVDTRawData) - 1 \\ \quad \left\| \begin{aligned} m_i &\leftarrow \frac{(LVDTC_i - LVDTR_i)}{k} \\ n_i &\leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ l_i &\leftarrow \frac{(LVDTR_i - LVDTL_i)}{q} \end{aligned} \right. \\ \text{augment}(m, n, l) \end{cases}$$

$$Rot4P3S2B0 := \text{augment}\left(\text{medsmooth}\left(Tilt(7.1, 7.8)^{(0)}, 99\right), \text{medsmooth}\left(Tilt(7.1, 7.8)^{(1)}, 99\right), \text{medsmooth}\left(Tilt(7.1, 7.8)^{(2)}, 99\right)\right)$$

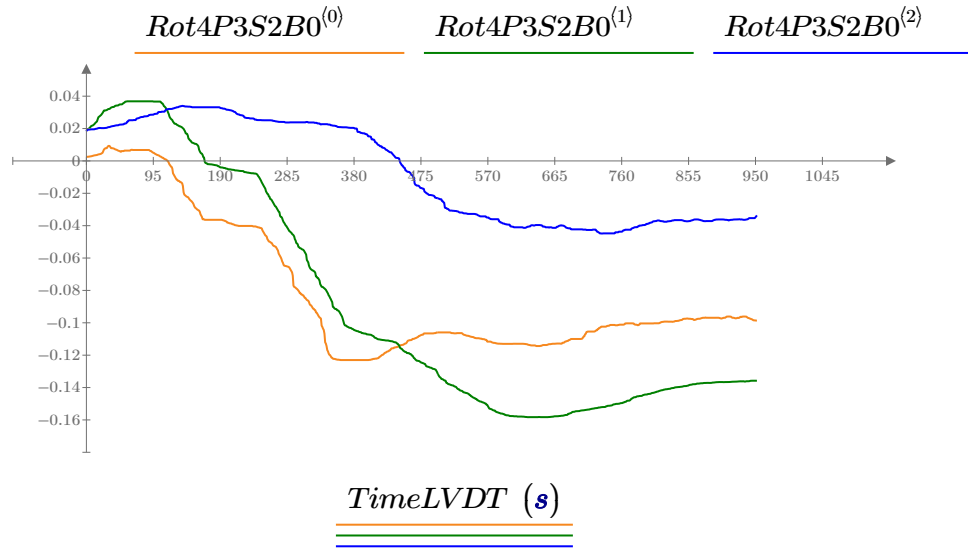


Fig C 14. LVDT rotations time history for pile group 4PS2B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

1. Introduction

The series of sheets in Appendix D contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P3S3B10 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

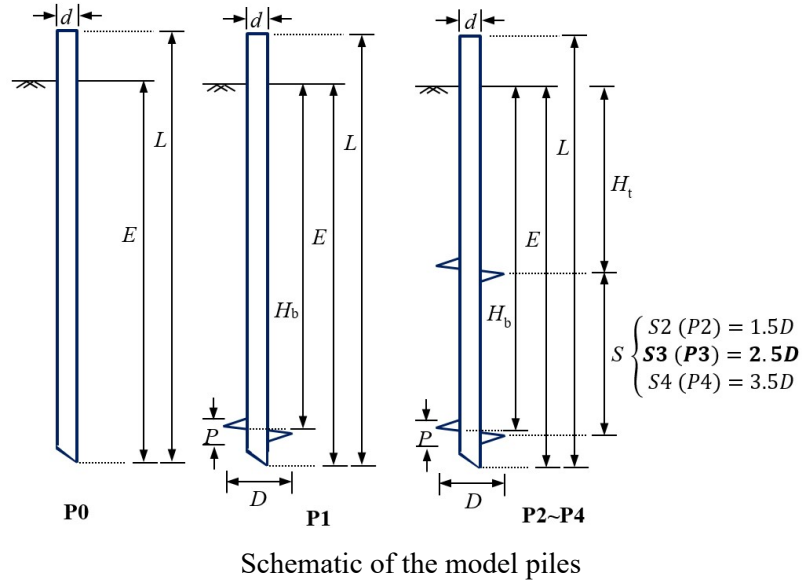
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P3= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \frac{kN \cdot m}{V}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \quad \quad \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & SG1_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG2_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG3_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG4_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(SG1^{(0)}, \text{smthn}), \text{medsmooth}(SG2^{(1)}, \text{smthn}), \text{medsmooth}(SG3^{(2)}, \text{smthn}), \text{medsmooth}(SG4^{(3)}, \text{smthn}))
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{cases} \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \mathbf{8} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \quad \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow -(\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{cases}
 \end{aligned}$$

Appendix D

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$G4P3S3B10HBM := \text{READExcel}(\text{".\3P3B10G.xlsx"}, \text{"Sheet1 (2)!A3:M8603"})$

$\text{TimeDisp}G4P3S3B10 := \text{TimeZero}(G4P3S3B10HBM)$

$AxLdG4P3S3B10 := \text{ConvLd}(G4P3S3B10HBM, 3, CFAxl, 11, 1)$

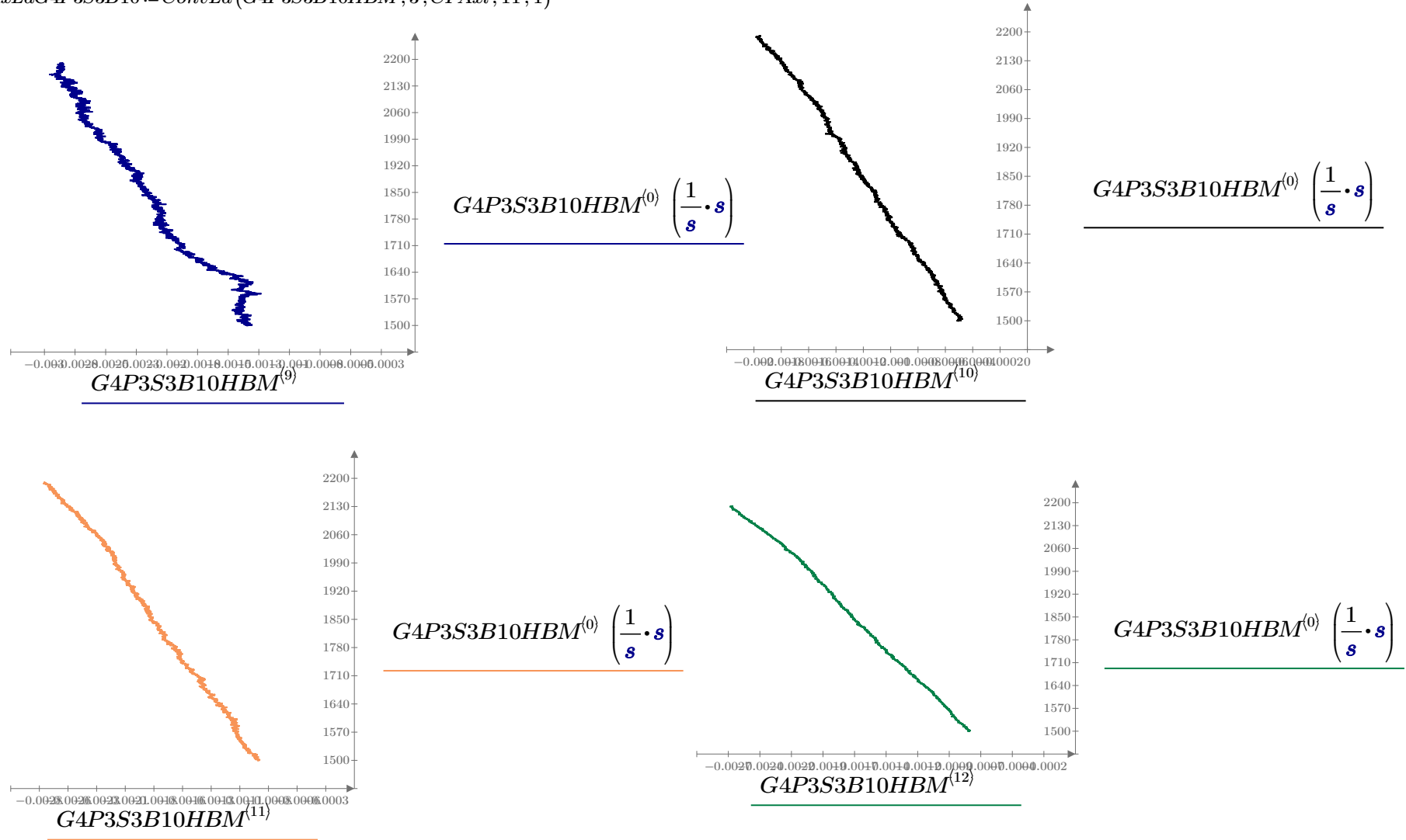


Fig D 1. Rawdata axial load time history for pile group 4P3S3B10

Appendix D

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

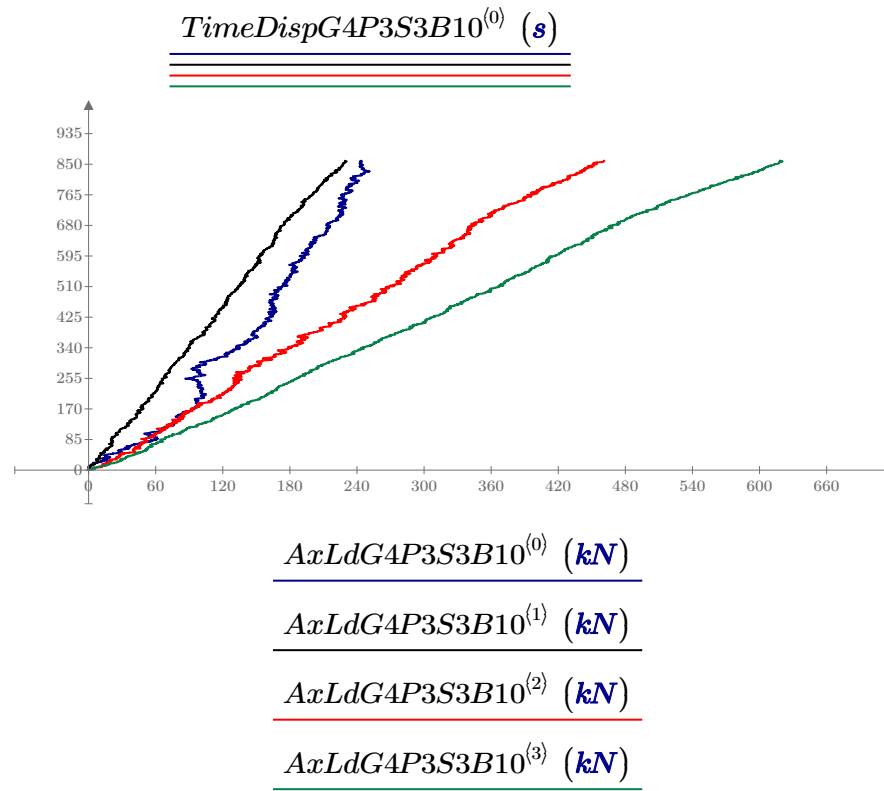


Fig D 2. Axial Load time history for pile group 4P3S3B10

Appendix D Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

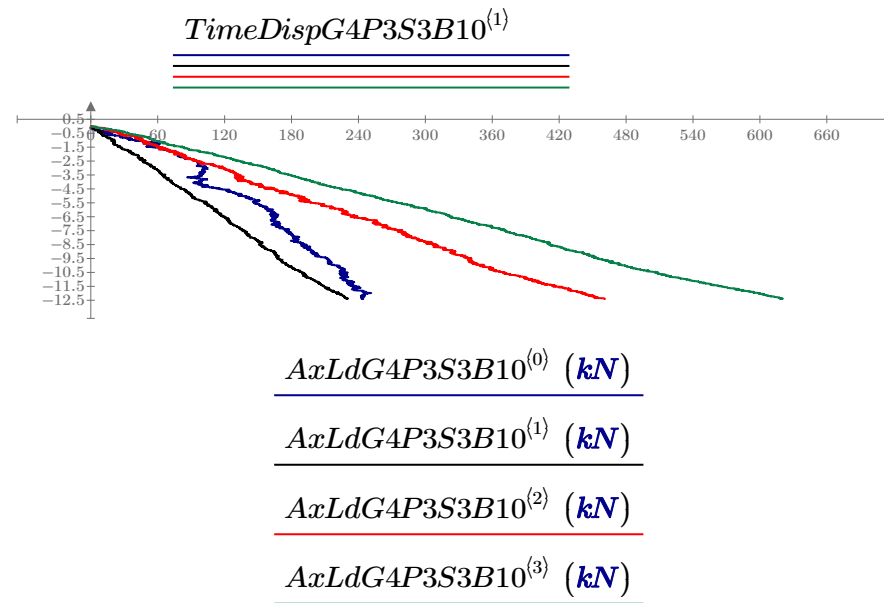


Fig D 3. Axial Load -displacement for pile group 4P3S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SCplotQP (AzLdG4P3S2B0, TimeDispG4P3S2B0, PileNum) =
QP0 ← if PileNum = 0
    | augment (lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−15, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−20, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”))
    | else
    | augment (lookup (−2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), “near”))
QP1 ← if PileNum = 0
    | augment (lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−15, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−20, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”))
    | else
    | augment (lookup (−2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(1), “near”))
QP2 ← augment (lookup (−2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), “near”), lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), “near”), lookup (−7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), “near”))
QP3 ← augment (lookup (−2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), “near”), lookup (−5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), “near”), lookup (−7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), “near”), lookup (−10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), “near”))
combined ← if PileNum = 0
    | stack (QP0, QP1, QP1, QP1, QP1, QP1)
    | else
    | stack (QP0, QP1, QP1, QP2, QP2, QP3)
combined

```

$$Qdist4P3S3B10 := SGplotQP(AxLdG4P3S3B10, TimeDispG4P3S3B10, 3) = \begin{bmatrix} 96.3282 & 133.8128 & 176.2482 & 221.0882 \\ 48.3547 & 89.9539 & 137.0642 & 177.0634 \\ 48.3547 & 89.9539 & 137.0642 & 177.0634 \\ 96.0342 & 185.2494 & 276.4535 & 353.1672 \\ 96.0342 & 185.2494 & 276.4535 & 353.1672 \\ 131.1707 & 252.625 & 372.2109 & 478.3433 \end{bmatrix} \quad \mathbb{KN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{selfac_{0,0}} \quad \begin{bmatrix} 131.1707 & 252.625 & 372.2109 & 478.3433 \end{bmatrix}$$

SG embedding depth in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 5 represents depth to strain SG 1 to 4

Appendix D Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

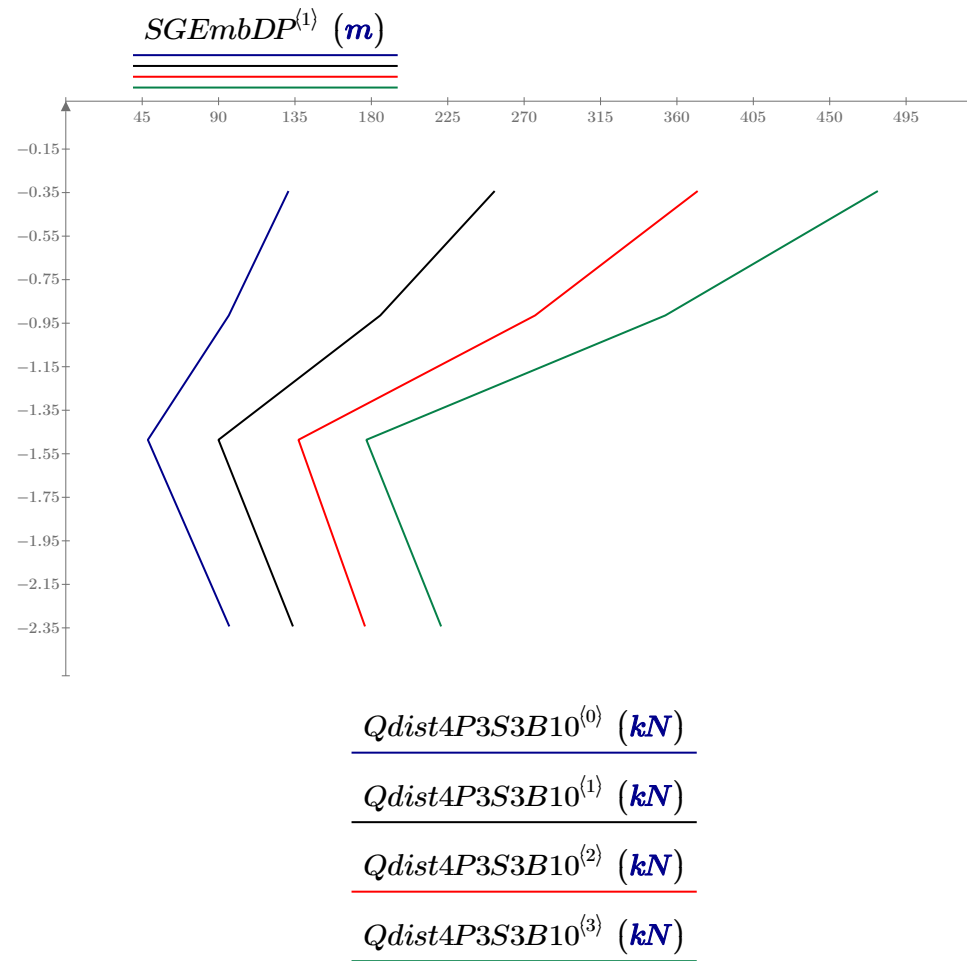
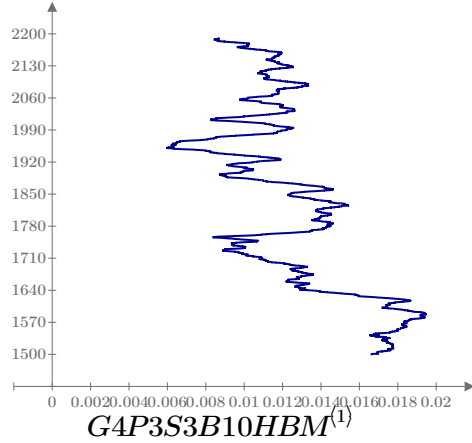


Fig D 4. Axial Load -displacement for pile group 4P3S3B10

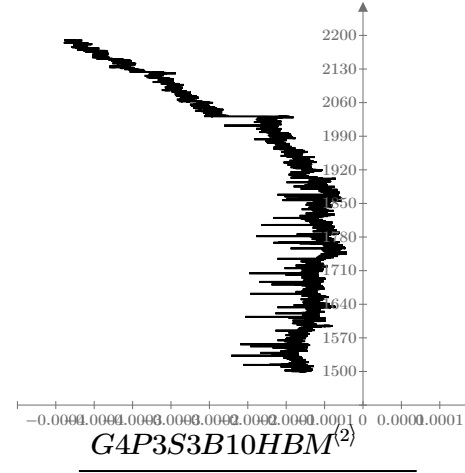
2.3.3 Bending Moment vs Time

$BM1_{G4P3S3B10} := ConvLd(G4P3S3B10HBM, 3, CFBM, 111, 2)$

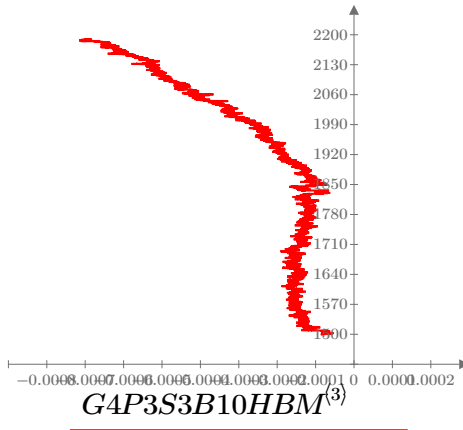
$BM2_{G4P3S3B10} := ConvLd(G4P3S3B10HBM, 5, CFBM, 77, 3)$



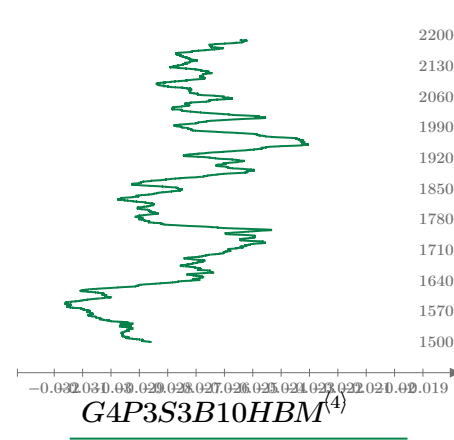
$$\underline{G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



$$\underline{G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$

Fig D 5. Raw Data Bending Moment 1 for pile group 4P3S3B10

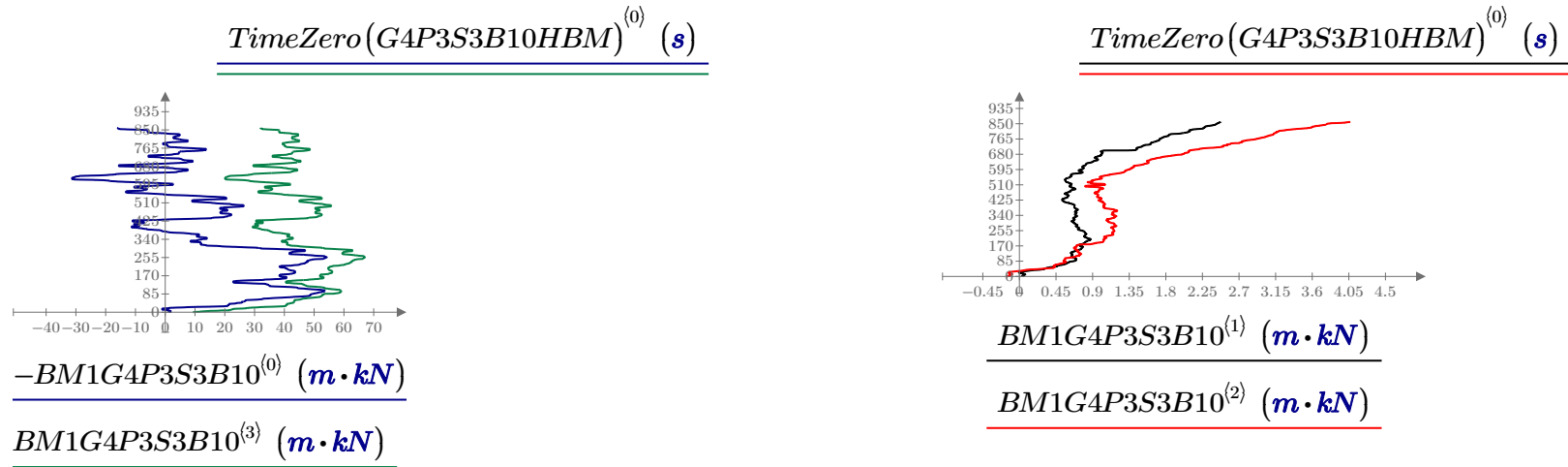


Fig D 6. Bending Moment 1 time history for pile group 4P3S3B10

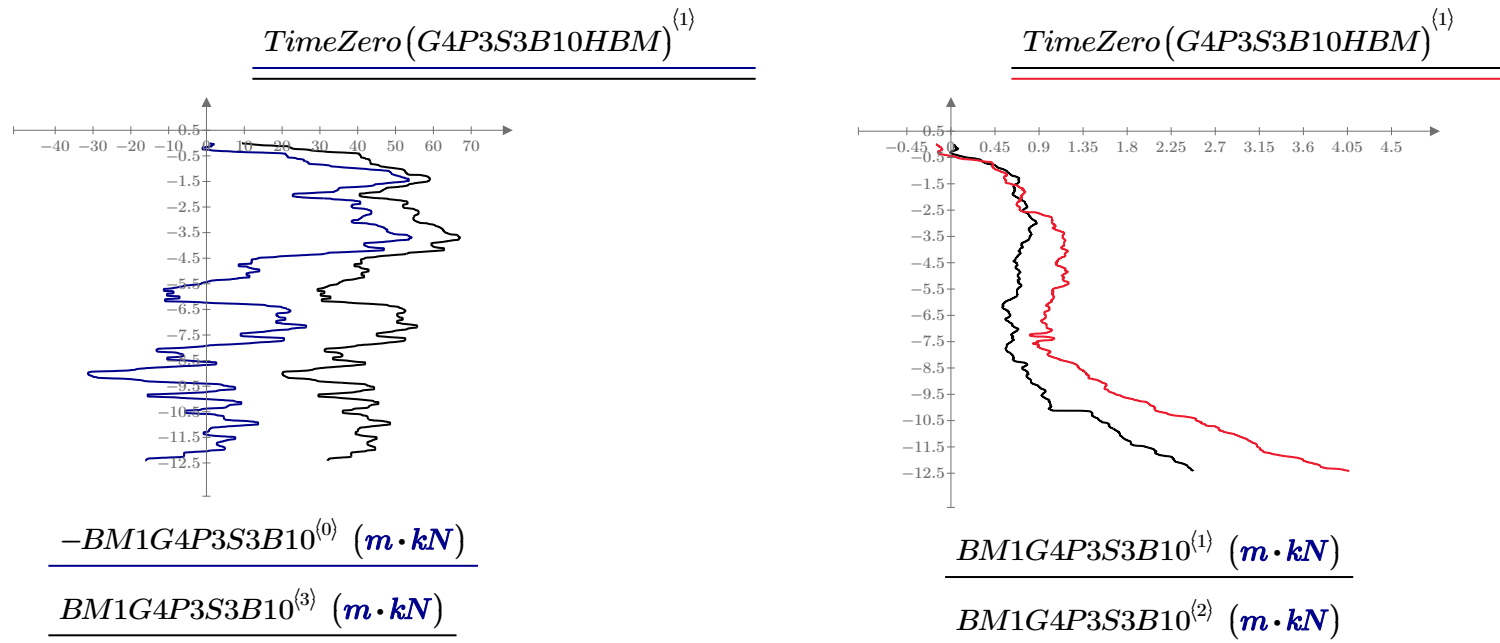


Fig D 7. Bending Moment 1 - displacement for pile group 4P3S3B10

Appendix D

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

$$BMM_{axdist4P3S3B10} := SGplotQP(BM1G4P3S3B10, TimeDispG4P3S3B10, 3) = \begin{bmatrix} -38.5146 & -13.9659 & -9.0467 & 0.801 \\ 0.7351 & 0.6826 & 0.6226 & 1.0202 \\ 0.7351 & 0.6826 & 0.6226 & 1.0202 \\ 0.7059 & 1.1402 & 0.8765 & 2.0788 \\ 0.7059 & 1.1402 & 0.8765 & 2.0788 \\ 52.0864 & 42.8693 & 45.0188 & 38.8877 \end{bmatrix} \quad m \cdot kN$$

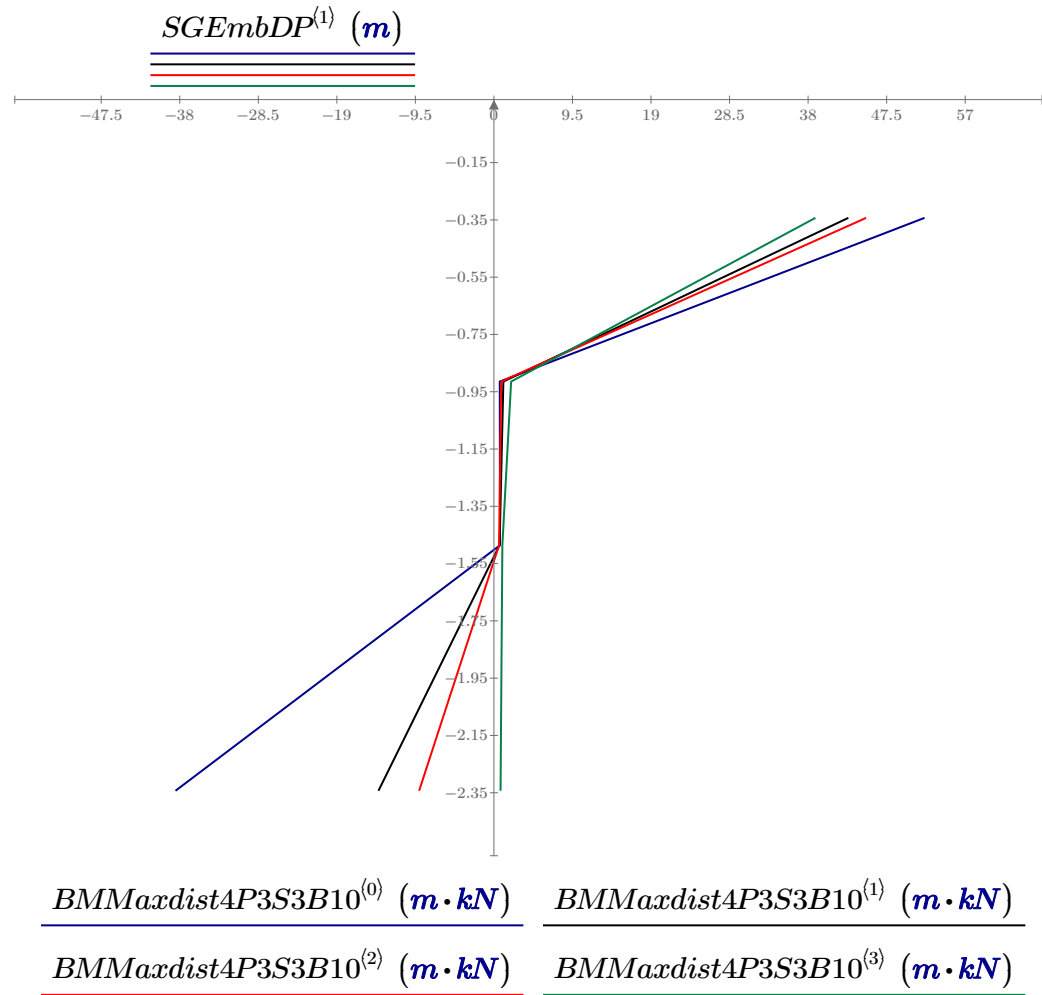
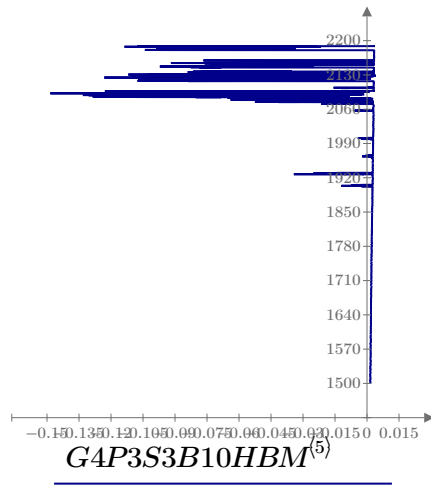
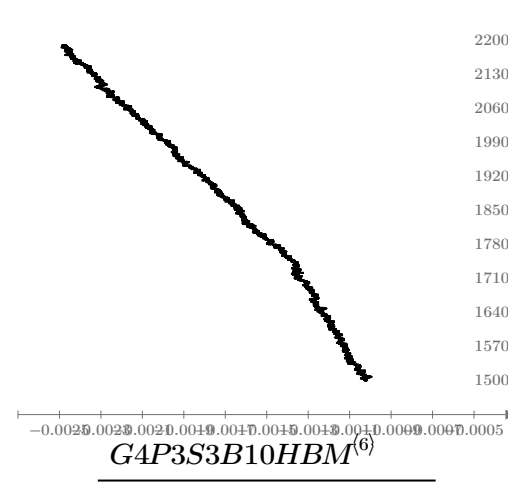


Fig D 8. Bending Moment 1 - depth for pile group 4P3S3B10

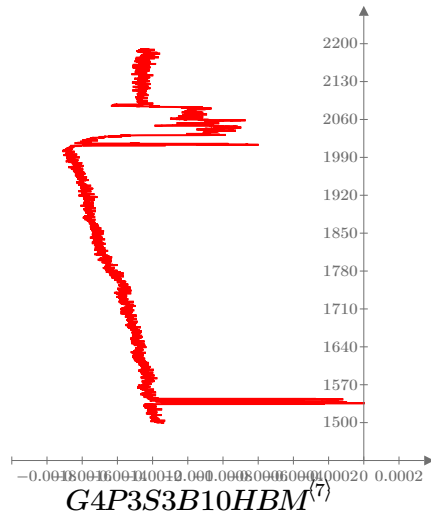
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group



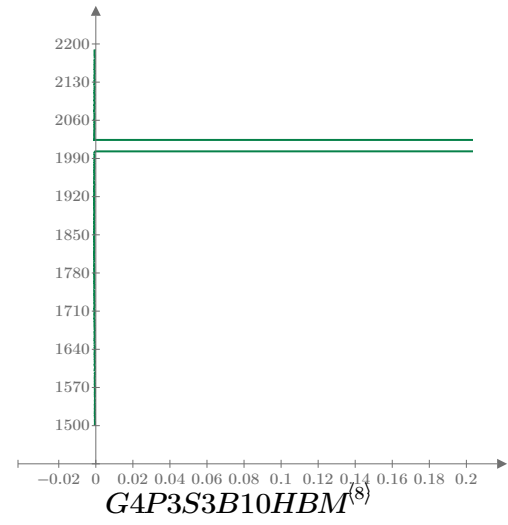
$$G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



$$G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



$$G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



$$G4P3S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$

Fig D 9. Raw Data Bending Moment 2 for pile group 4P3S3B10

Appendix D
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

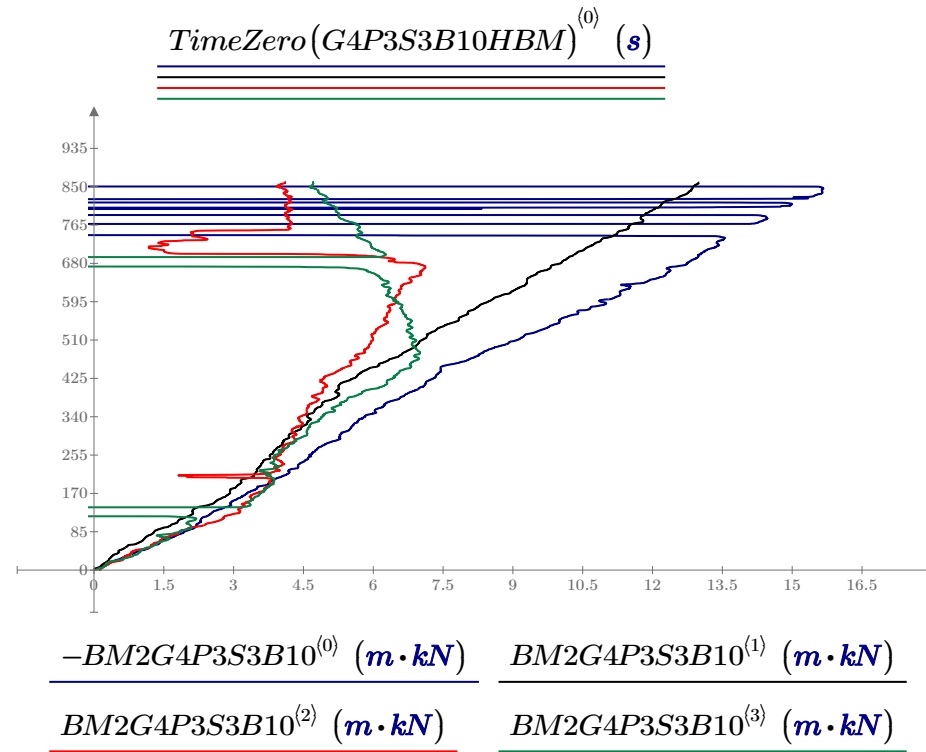


Fig D 10. Bending Moment 2 time history for pile group 4P3S3B10

Appendix D

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

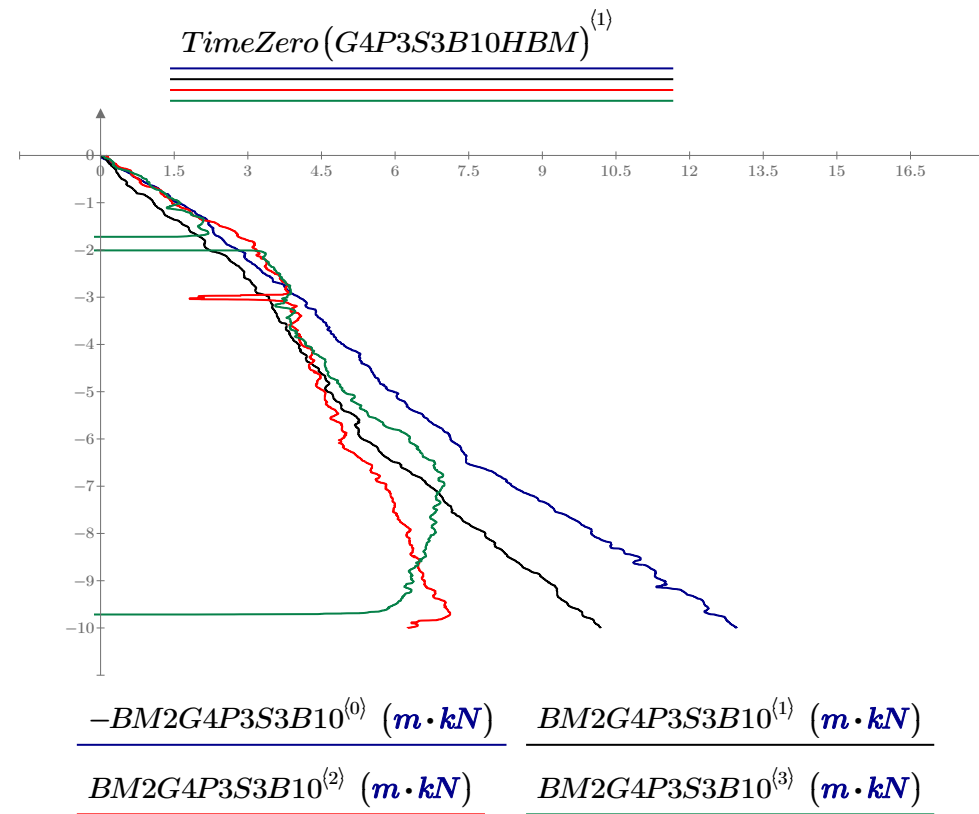


Fig D 11. Bending Moment 2 - displacement for pile group 4P3S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

$$BMM_{indist4P3S3B10} := SGplotQP(BM2G4P3S3B10, TimeDispG4P3S3B10, 3) = \begin{bmatrix} -3.3506 & -5.9776 & -9.239 & -12.9663 \\ 2.9207 & 4.6211 & 7.1516 & 10.1923 \\ 2.9207 & 4.6211 & 7.1516 & 10.1923 \\ 3.5453 & 4.5582 & 5.9764 & 6.2499 \\ 3.5453 & 4.5582 & 5.9764 & 6.2499 \\ 3.6383 & 4.9531 & 6.8572 & -5608.6471 \end{bmatrix} \quad \text{m} \cdot \text{kN}$$

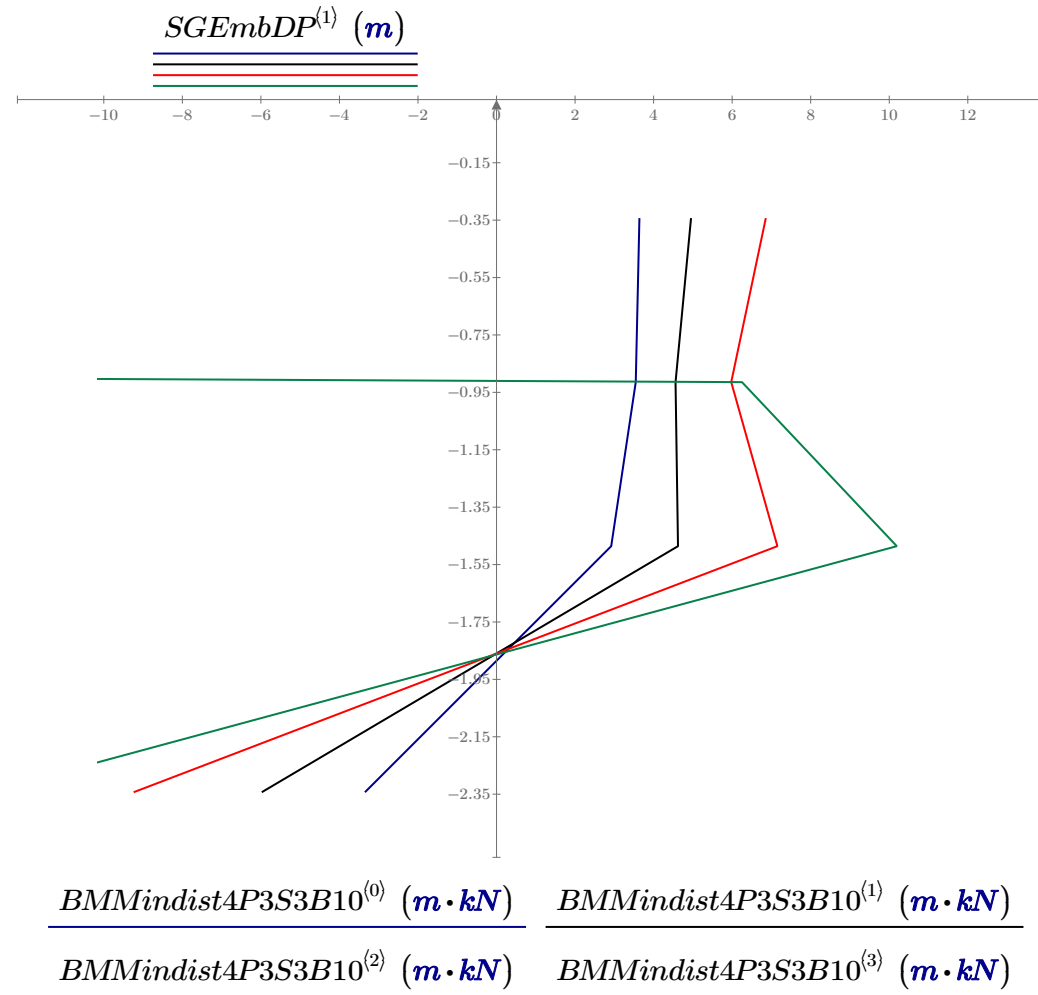


Fig D 12. Bending Moment 2 - depth for pile group 4P3S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT (LVDTRawData, smthn) := || TimeLVDT ← submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 0, 0) s
                             || LVDT1 ← medsmooth (submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 1, 1) mm, smthn)
                             || LVDT2 ← medsmooth (submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 2, 2) mm, smthn)
                             || for i ∈ 0, 1..rows (LVDTRawData) - 1
                             ||   k_i ← (TimeLVDT_i - TimeLVDT_0)
                             ||   q_i ← -(LVDT1_i - LVDT1_0) · 2 · Nscalescifac0,0
                             ||   m_i ← -(LVDT2_i - LVDT2_0) · 2 · Nscalescifac0,0
                             ||   n_i ← -(TimeLVDT_i - TimeLVDT_0) · CmpRate · Nscalescifac0,0
                             || augment (k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-3P3B10G.xlsx"}, \text{"Sheet1 (2)!A2:C862"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

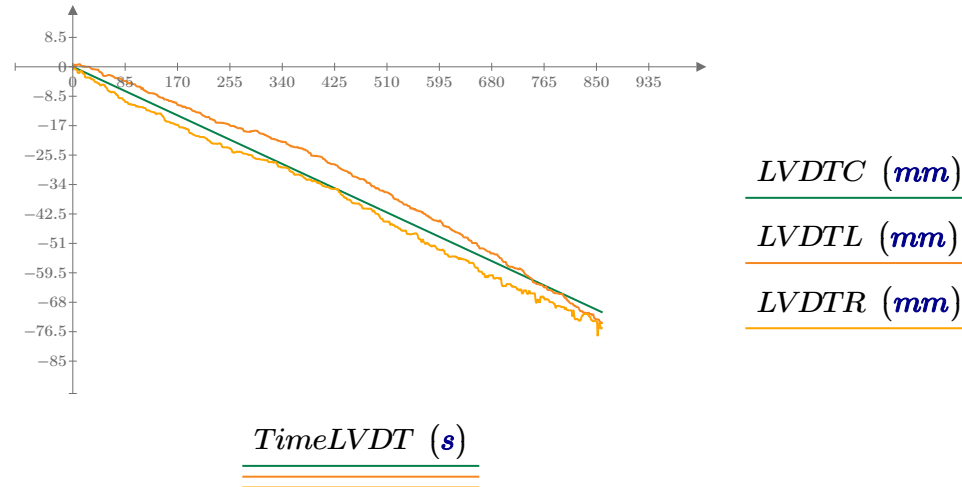


Fig D 13. LVDT displacements time history for pile group 4PS3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B10 Helix Pile Group

Function for determining the tilting of the plate

```

Tilt (SpacingDCDLR, SpacingDLDR) :=
  k ← (SpacingDCDLR) • mm • Nscalescifac0,0
  q ← (SpacingDLDR) • mm • Nscalescifac0,0
  for i ∈ 0, 1 .. rows (LVDTRawData) - 1
    mi ←  $\frac{(LVDTC_i - LVDTR_i)}{k}$ 
    ni ←  $\frac{(LVDTC_i - LVDTL_i)}{k}$ 
    li ←  $\frac{(LVDTR_i - LVDTL_i)}{q}$ 
  augment (m, n, l)
  
```

$Rot4P3S3B10 := \text{augment} \left(\text{medsmooth} \left(Tilt(7.1, 7.8)^{(0)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(1)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(2)}, 99 \right) \right)$

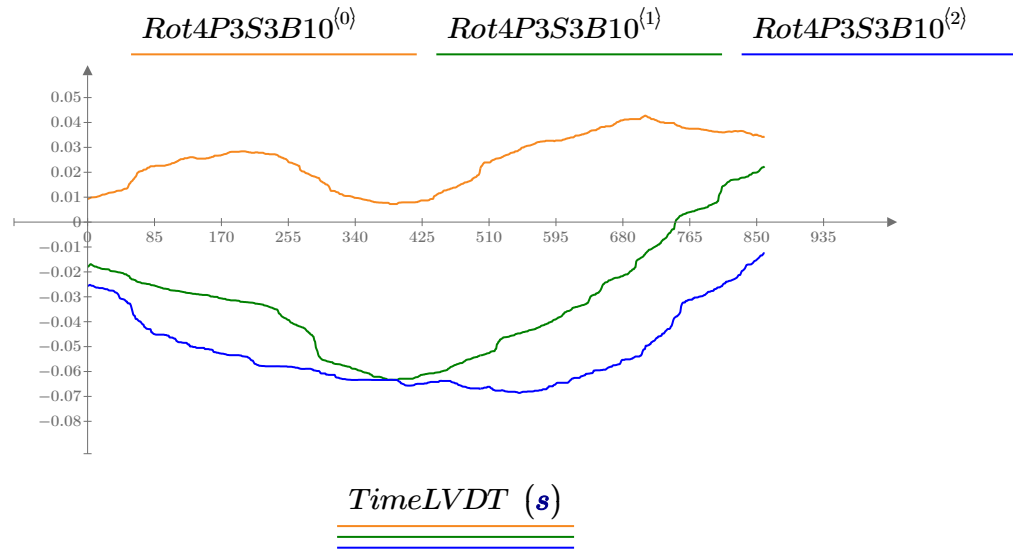


Fig D 14. LVDT rotations time history for pile group 4PS3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

1. Introduction

The series of sheets in Appendix E contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P0S3B10 Smooth Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

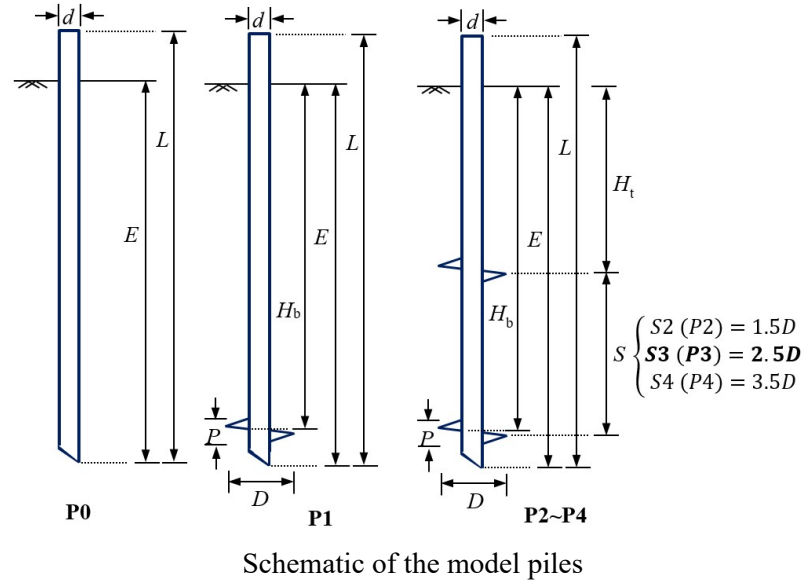
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P3= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := submatrix(RawDataCalib, 0, rows(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots rows(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots cols(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ \quad \quad k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ \quad \quad l_{i,j} \leftarrow CmbMArm_{i,0} \\ \quad \quad q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ \quad \quad m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad \quad \quad 0 \\ \quad \quad \quad \text{else} \\ \quad \quad \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{matrix} \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \\ \frac{kN \cdot m}{V} \\ \frac{mV}{V} \end{matrix}$$

Calibration Factor. Here, the columns represents the Piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \quad \quad \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & SG1_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG2_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG3_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & SG4_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(SG1^{(0)}, \text{smthn}), \text{medsmooth}(SG2^{(1)}, \text{smthn}), \text{medsmooth}(SG3^{(2)}, \text{smthn}), \text{medsmooth}(SG4^{(3)}, \text{smthn}))
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{cases} \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \mathbf{8} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \quad \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow -(\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{d} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{cases}
 \end{aligned}$$

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

There were two strain gages placed within the P0 pile. The following sub sections provides the details on the load distributions:

$G4P0S3B10HBM := \text{READExcel}(\text{".\3P0B10G.xlsx"}, \text{"Sheet1 (2)!A3:M8263"})$

$\text{TimeDisp}G4P0S3B10 := \text{TimeZero}(G4P0S3B10HBM)$

$AxLdG4P0S3B10 := \text{ConvLd}(G4P0S3B10HBM, 0, CFAxl, 11, 1)$

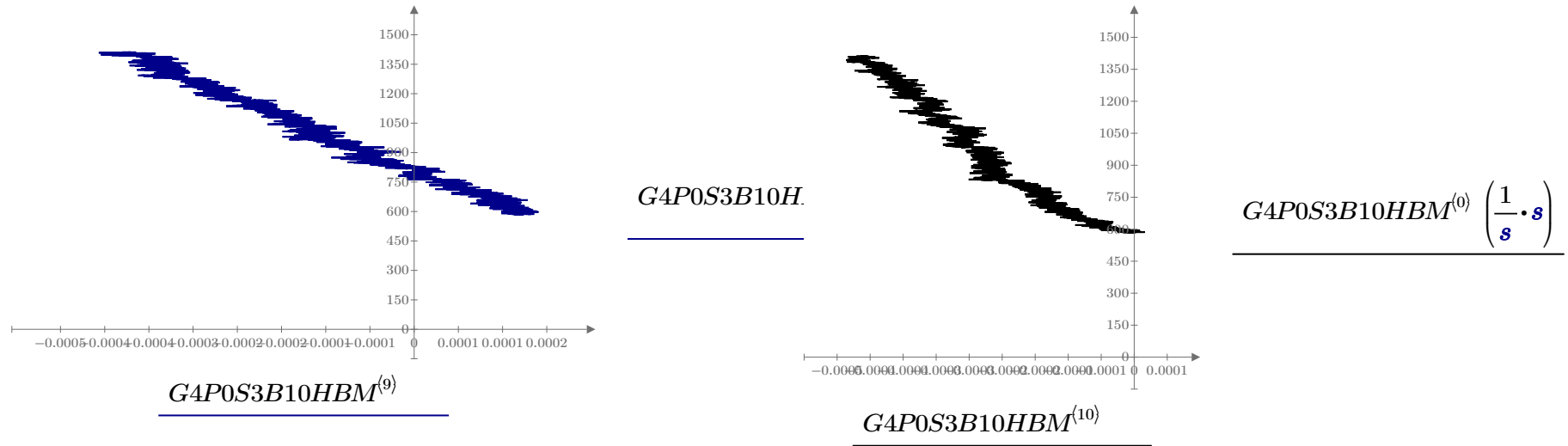


Fig E 1. Rawdata axial load time history for pile group 4P0S3B10

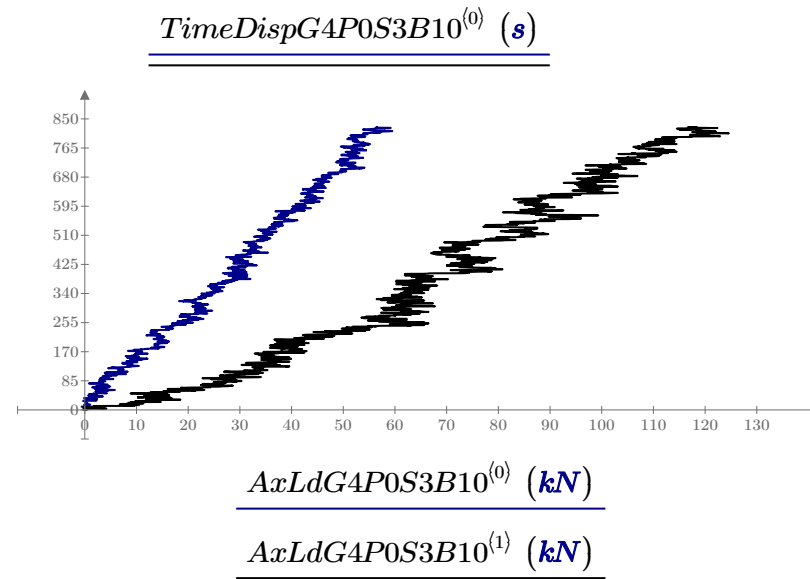


Fig E 2. Axial Load time history for pile group 4P0S3B10

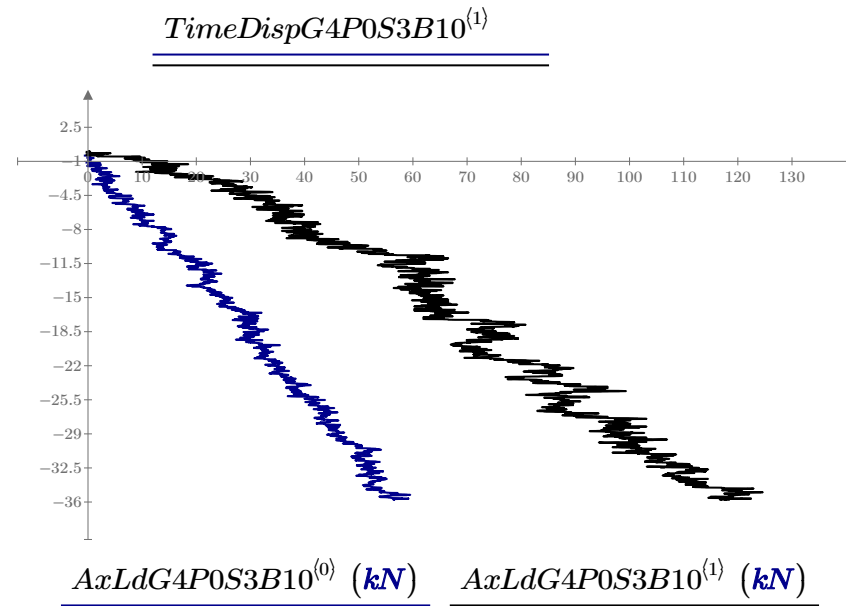


Fig E 3. Axial Load -displacement for pile group 4P0S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SGplotQP (AxLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  QP1 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near" , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near" , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near"))
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near" , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near" , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near" , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near"))
  combined ← if PileNum = 0
    stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  else
    stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  combined

```

$$Qdist4P0S3B10 := SGplotQP (AxLdG4P0S3B10 , TimeDispG4P0S3B10 , 0) = \begin{bmatrix} 6.4765 & 13.8781 & 25.4432 & 32.6907 \\ 31.156 & 54.3125 & 65.2591 & 69.8904 \\ 31.156 & 54.3125 & 65.2591 & 69.8904 \\ 31.156 & 54.3125 & 65.2591 & 69.8904 \\ 31.156 & 54.3125 & 65.2591 & 69.8904 \\ 31.156 & 54.3125 & 65.2591 & 69.8904 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{sclfac}_{0,0}$$

SG embedment depth in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 5 represents depth to strain SG 1 to 4

Appendix E Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

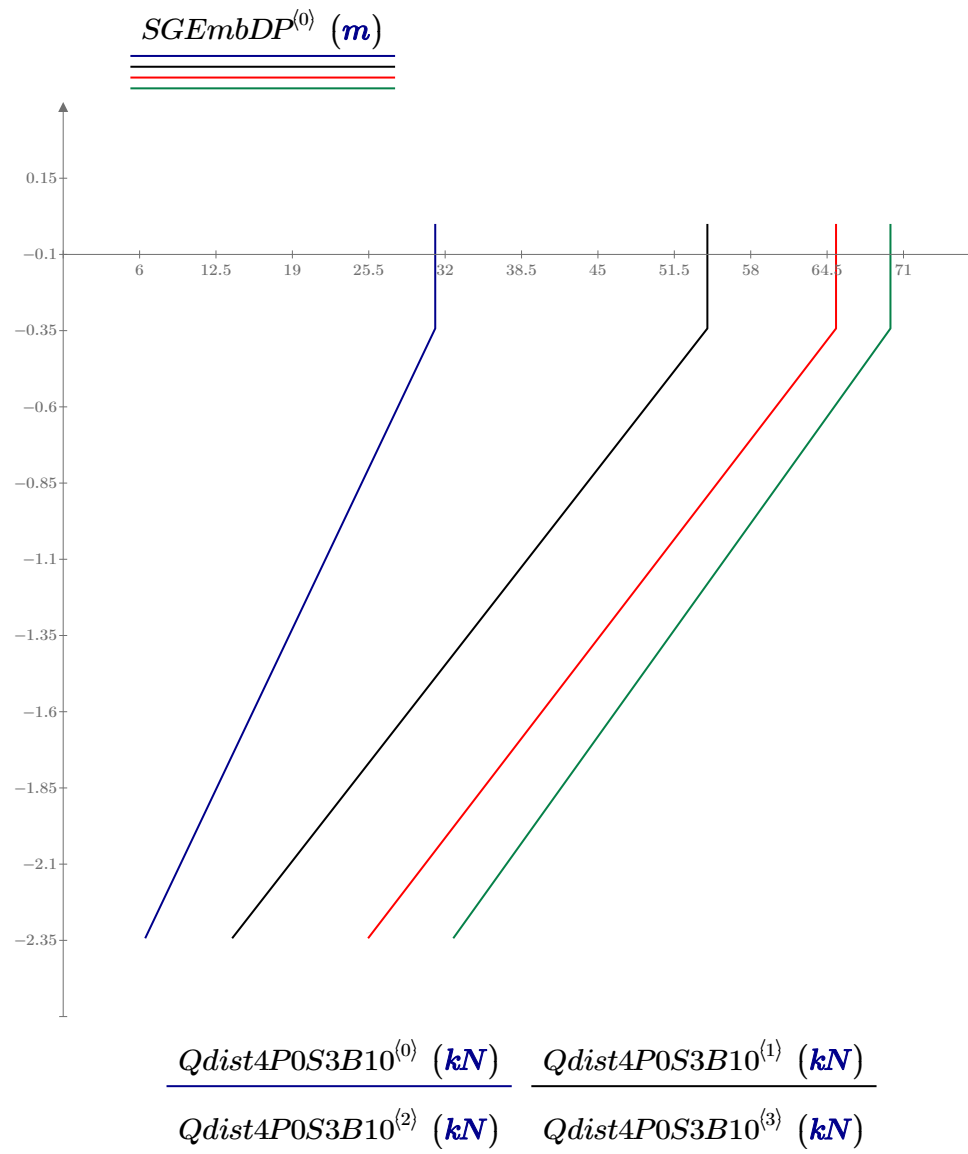
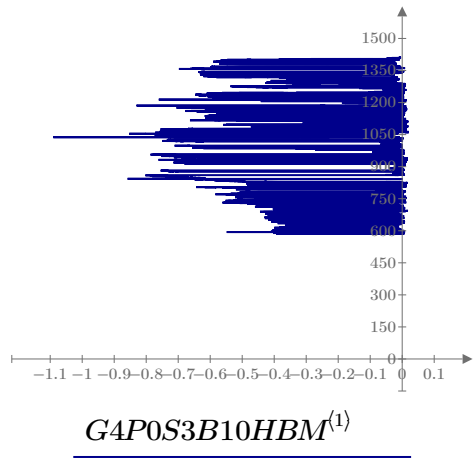


Fig E 4. Axial Load -depth for pile group 4P0S3B10

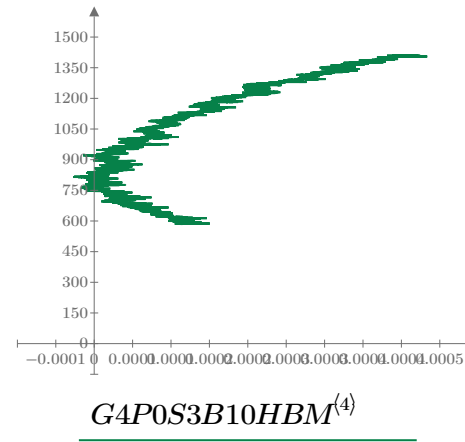
2.3.3 Bending Moment vs Time

$BM1G4P0S3B10 := ConvLd(G4P0S3B10HBM, 1, CFBM, 999, 2)$

$BM2G4P0S3B10 := ConvLd(G4P0S3B10HBM, 0, CFBM, 999, 3)$

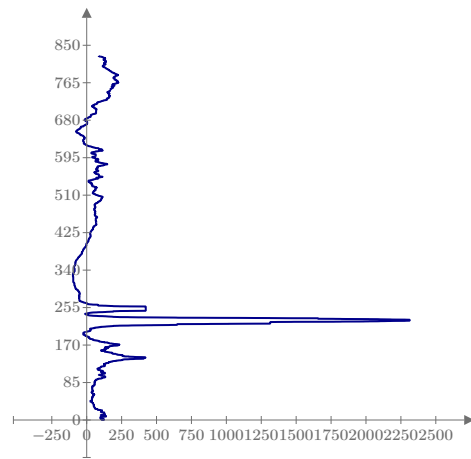


$$\underline{G4P0S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$



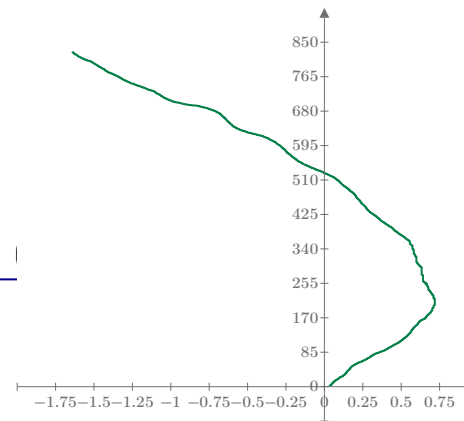
$$\underline{G4P0S3B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}$$

Fig E 5. Raw Data Bending Moment 1 for pile group 4P0S3B10



$BM1G4P0S3B10^{(0)} \text{ (m} \cdot \text{kN)}$

$TimeDispG4P0S3B10^{(0)}$

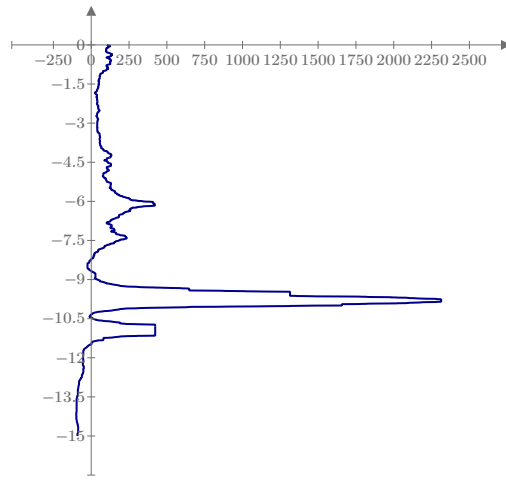


$BM1G4P0S3B10^{(3)} \text{ (m} \cdot \text{kN)}$

$TimeDispG4P0S3B10^{(0)} \text{ (s)}$

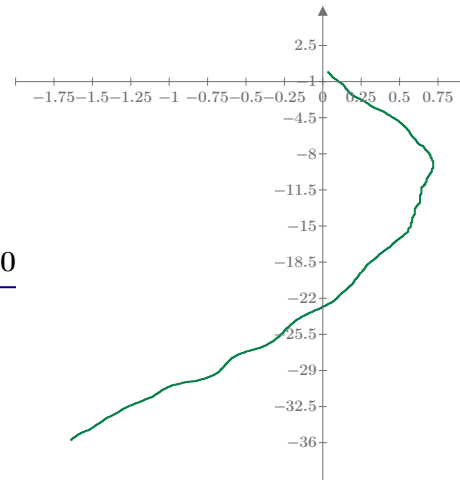
Fig E 6. Bending Moment 1 time history for pile group 4P0S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group



$TimeDispG4P0S3B10$

$BM1G4P0S3B10^{(0)} (m \cdot kN)$



$TimeDispG4P0S3B10^{(1)}$

$BM1G4P0S3B10^{(3)} (m \cdot kN)$

Fig E 7. Bending Moment 1 - displacement for pile group 4P0S3B10

```
SGplotQP (AzLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(0) , "near"))
  QP1 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near"))
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(2) , "near"))
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AzLdG4P3S2B0(3) , "near"))
  combined ← if PileNum = 0
    stack (QP0 , QP1 , QP1 , QP1 , QP1)
  else
    stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  combined
```

$BMMaxdist4P0S2B0 := SGplotQP (BM1G4P0S3B10 , TimeDispG4P0S3B10 , 0) =$

79.7825	1465.366	-91.2355	70.3968
0.5048	0.6931	0.5733	0.2225
0.5048	0.6931	0.5733	0.2225
0.5048	0.6931	0.5733	0.2225
0.5048	0.6931	0.5733	0.2225

$m \cdot kN$

Appendix E
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

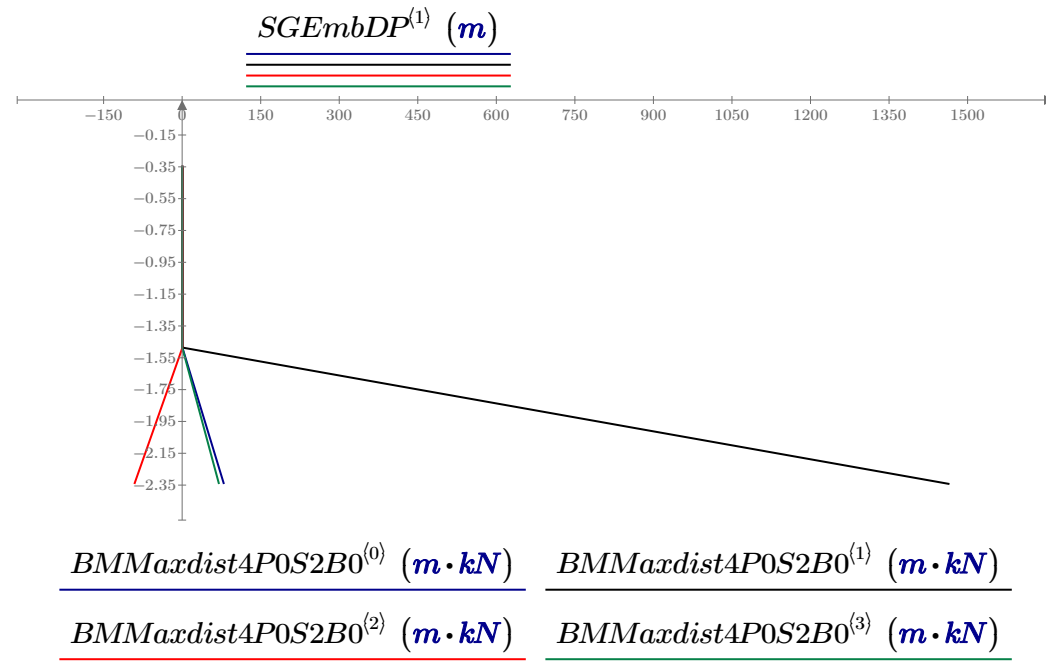


Fig E 8. Bending Moment 1 - depth for pile group 4P0S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

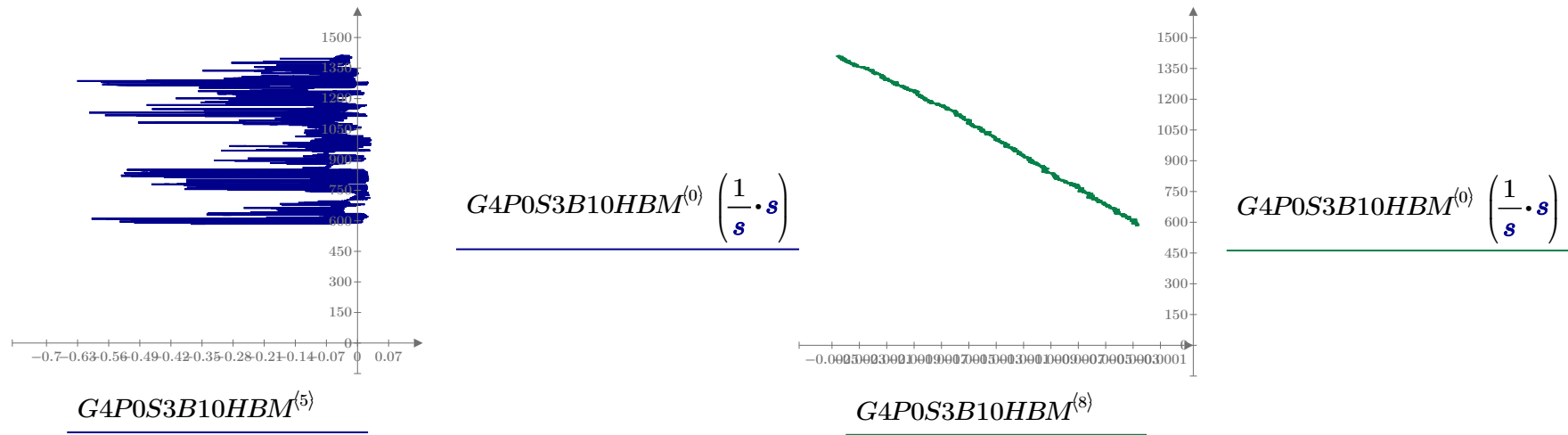


Fig E 9. Raw Data Bending Moment 2 for pile group 4P0S3B10

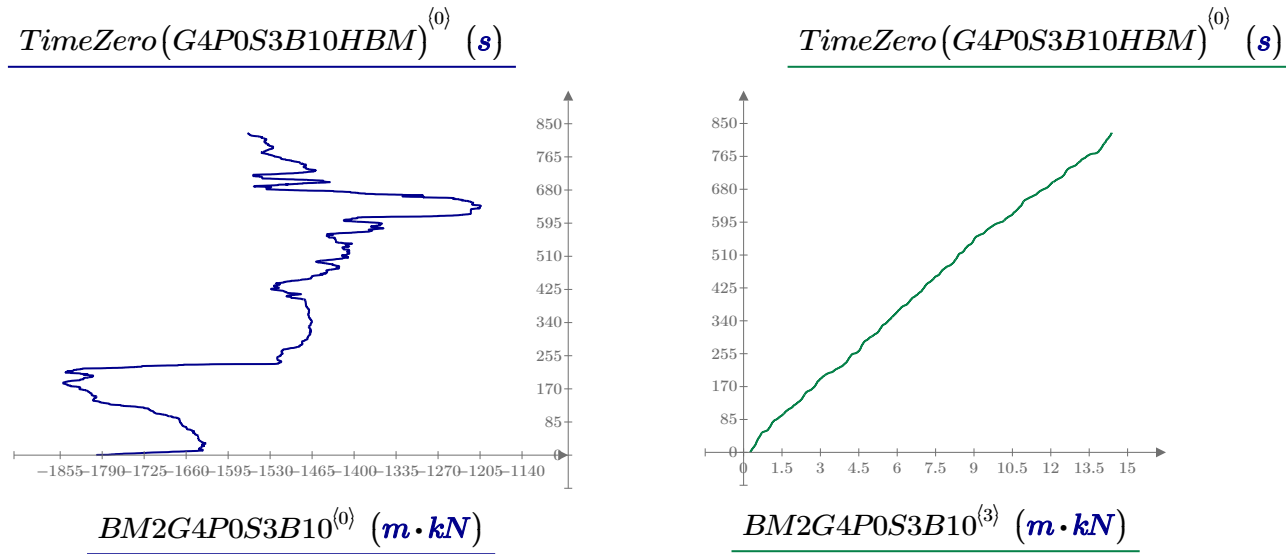


Fig E 10. Bending Moment 2 time history for pile group 4P0S3B10

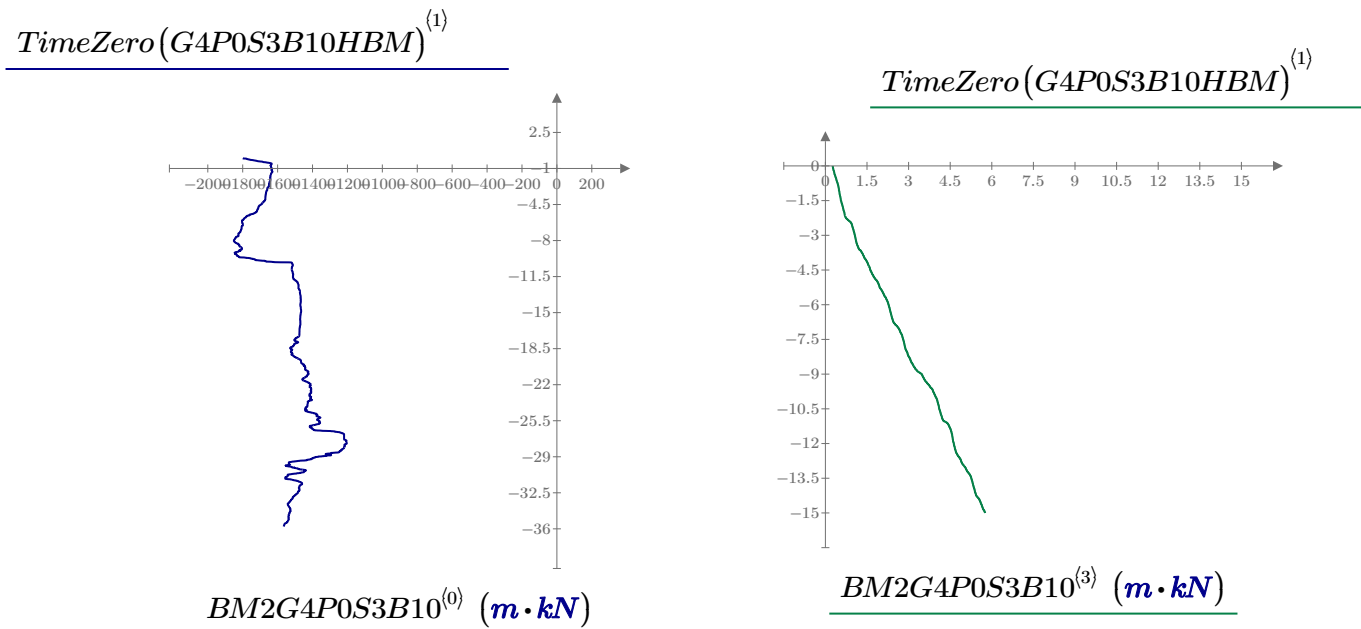


Fig E 11. Bending Moment 2 - displacement for pile group 4P0S3B10

Appendix E

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

$$BMMindist4P0S2B0 := SGplotQP(BM2G4P0S3B10, TimeDispG4P0S3B10, 0) = \begin{bmatrix} -1716.6308 & -1672.5733 & -1467.0388 & -1452.8049 \\ 1.8715 & 3.9867 & 5.7607 & 7.6711 \\ 1.8715 & 3.9867 & 5.7607 & 7.6711 \\ 1.8715 & 3.9867 & 5.7607 & 7.6711 \\ 1.8715 & 3.9867 & 5.7607 & 7.6711 \\ 1.8715 & 3.9867 & 5.7607 & 7.6711 \end{bmatrix} \text{ m} \cdot \text{kN}$$

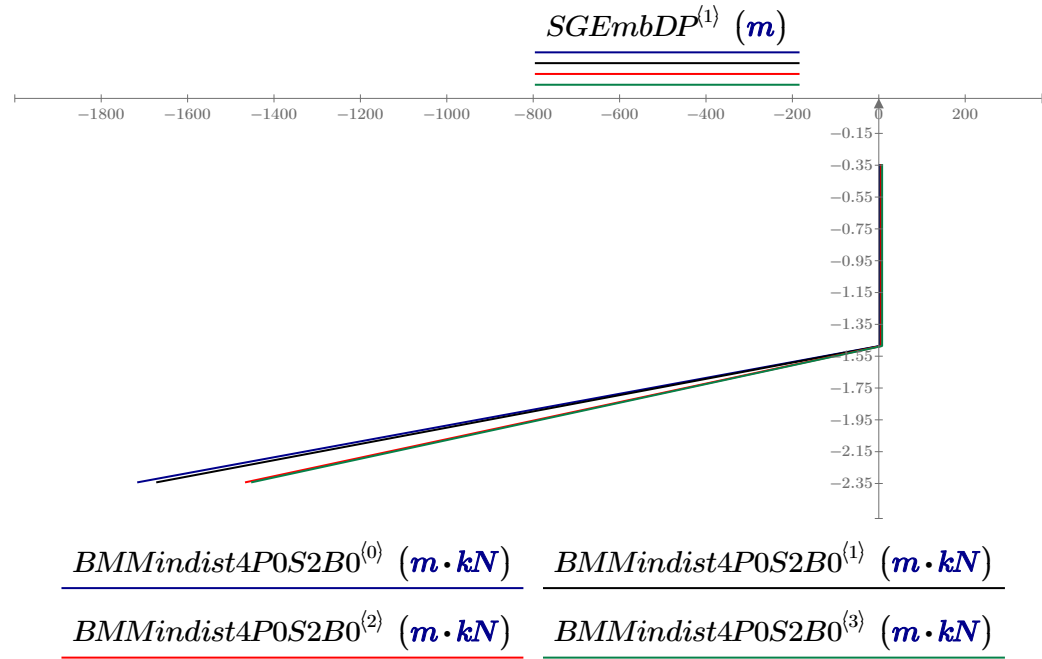


Fig E 12. Bending Moment 2 - depth for pile group 4P0S3B10

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) := || TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
                             || LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
                             || LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
                             || for i ∈ 0, 1..rows(LVDTRawData) - 1
                             ||   k_i ← (TimeLVDT_i - TimeLVDT_0)
                             ||   q_i ← -(LVDT1_i - LVDT1_0) • Nscalesclfac0,0
                             ||   m_i ← -(LVDT2_i - LVDT2_0) • Nscalesclfac0,0
                             ||   n_i ← -(TimeLVDT_i - TimeLVDT_0) • CmpRate • Nscalesclfac0,0
                             || augment(k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-3P0B10G.xlsx"}, \text{"Sheet1 (2)!A2:C828"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

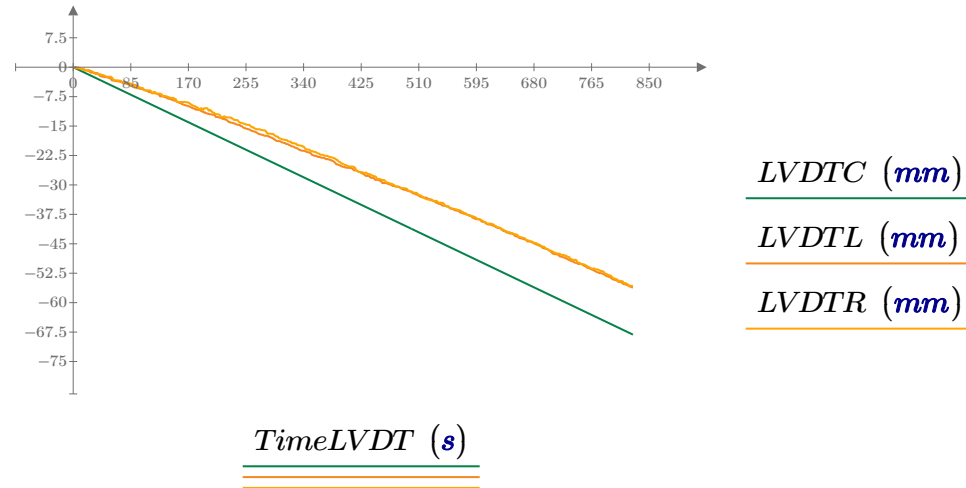


Fig E 13. LVDT displacements time history for pile group 4P0S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S3B10 Helix Pile Group

Function for determining the tilting of the plate

$$\begin{aligned}
 \text{Tilt}(\text{SpacingDCDLR}, \text{SpacingDLDR}) := & \begin{cases} k \leftarrow (\text{SpacingDCDLR}) \cdot \text{mm} \cdot \text{Nscale}^{sclfac}_{0,0} \\ q \leftarrow (\text{SpacingDLDR}) \cdot \text{mm} \cdot \text{Nscale}^{sclfac}_{0,0} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{LVDTRawData}) - 1 \\ \quad \left\| \begin{aligned} m_i &\leftarrow \frac{(LVDTC_i - LVDTR_i)}{k} \\ n_i &\leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ l_i &\leftarrow \frac{(LVDTR_i - LVDTL_i)}{q} \end{aligned} \right. \\ \text{augment}(m, n, l) \end{cases}
 \end{aligned}$$

$$\text{Rot4P0S3B10} := \text{augment}\left(\text{medsmooth}\left(\text{Tilt}(7.7, 7.8)^{(0)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.7, 7.8)^{(1)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.7, 7.8)^{(2)}, 99\right)\right)$$

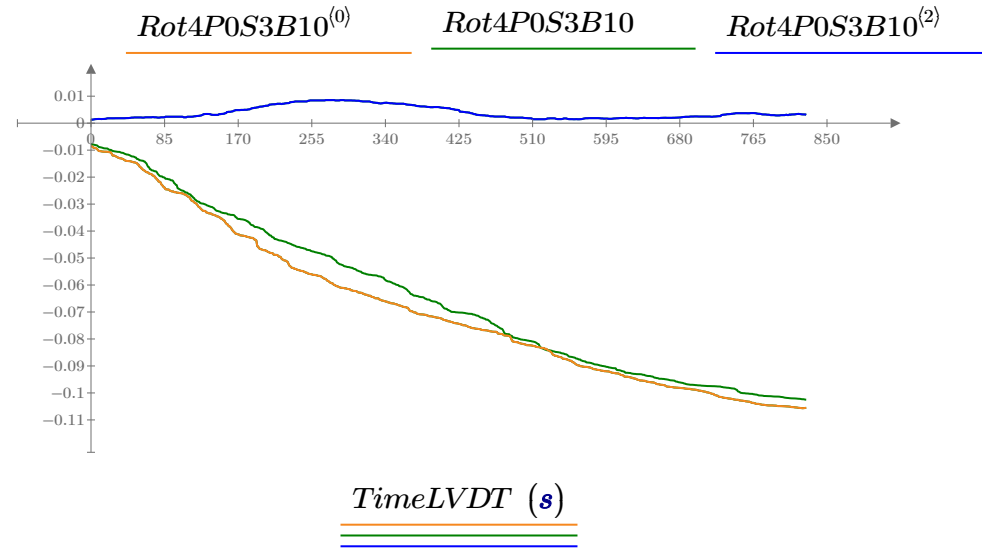


Fig E 14. LVDT rotations time history for pile group 4P0S3B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

1. Introduction

The series of sheets in Appendix F contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P3S3B0 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

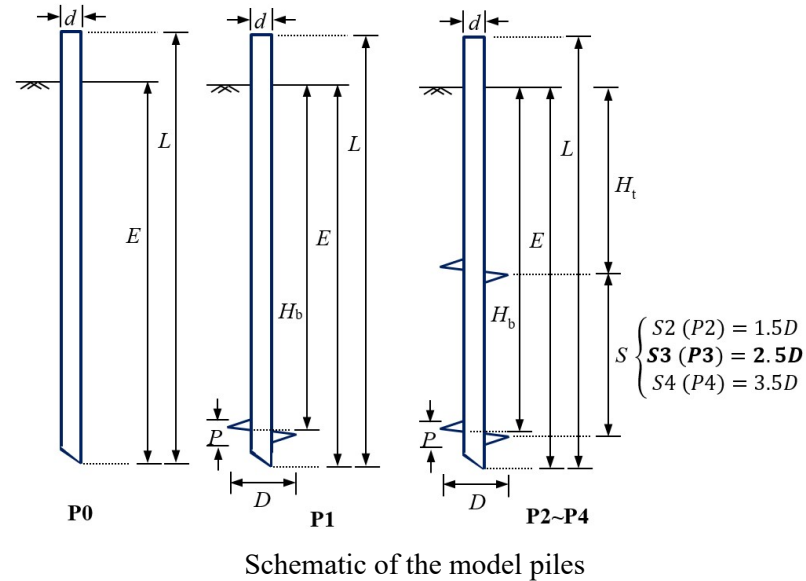
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg · g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) · $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{matrix} \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \\ \frac{kN \cdot m}{mV} \\ V \end{matrix}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \cdot \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \cdot \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \quad \quad \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & \text{SG1}_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG2}_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG3}_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG4}_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(\text{SG1}^{(0)}, \text{smthn}), \text{medsmooth}(\text{SG2}^{(1)}, \text{smthn}), \text{medsmooth}(\text{SG3}^{(2)}, \text{smthn}), \text{medsmooth}(\text{SG4}^{(3)}, \text{smthn}))
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{cases} \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \cdot 8 \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \quad \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow -(\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{cases}
 \end{aligned}$$

Appendix F

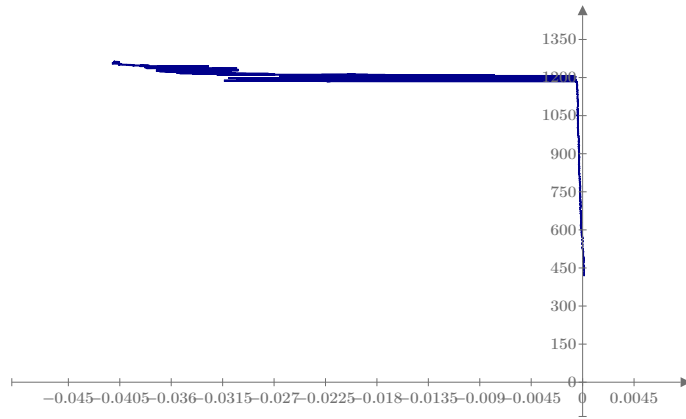
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

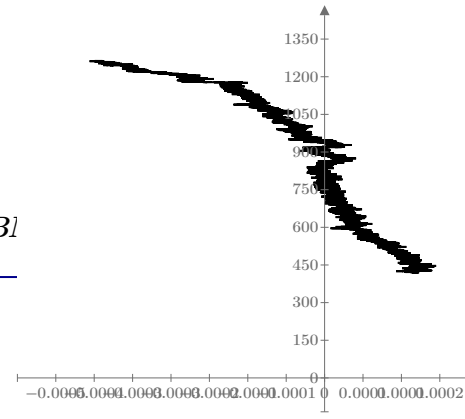
$G4P3S3B0HBM := \text{READExcel}(\text{".\3P3B0G.xlsx"}, \text{"Sheet1 (2)!A3:M8433"})$

$\text{TimeDispG4P3S3B0} := \text{TimeZero}(G4P3S3B0HBM)$

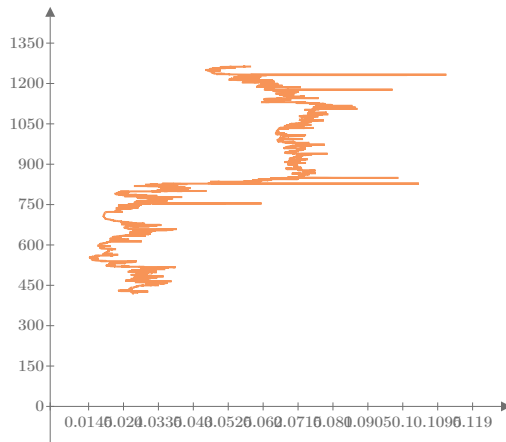
$\text{AxLdG4P3S3B0} := \text{ConvLd}(G4P3S3B0HBM, 3, \text{CF} \text{Axl}, 111, 1)$



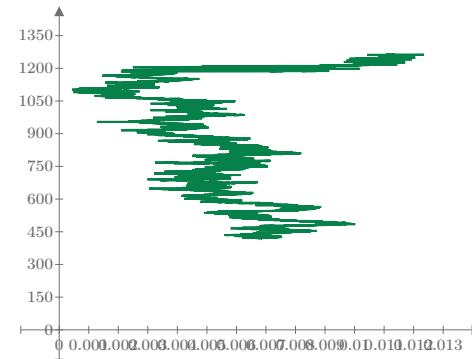
$G4P3S3B0HBM^{(9)}$



$G4P3S3B0HBM^{(10)}$



$G4P3S3B0HBM^{(11)}$



$G4P3S3B0HBM^{(12)}$

Fig F 1. Rawdata axial load time history for pile group 4P3S3B0

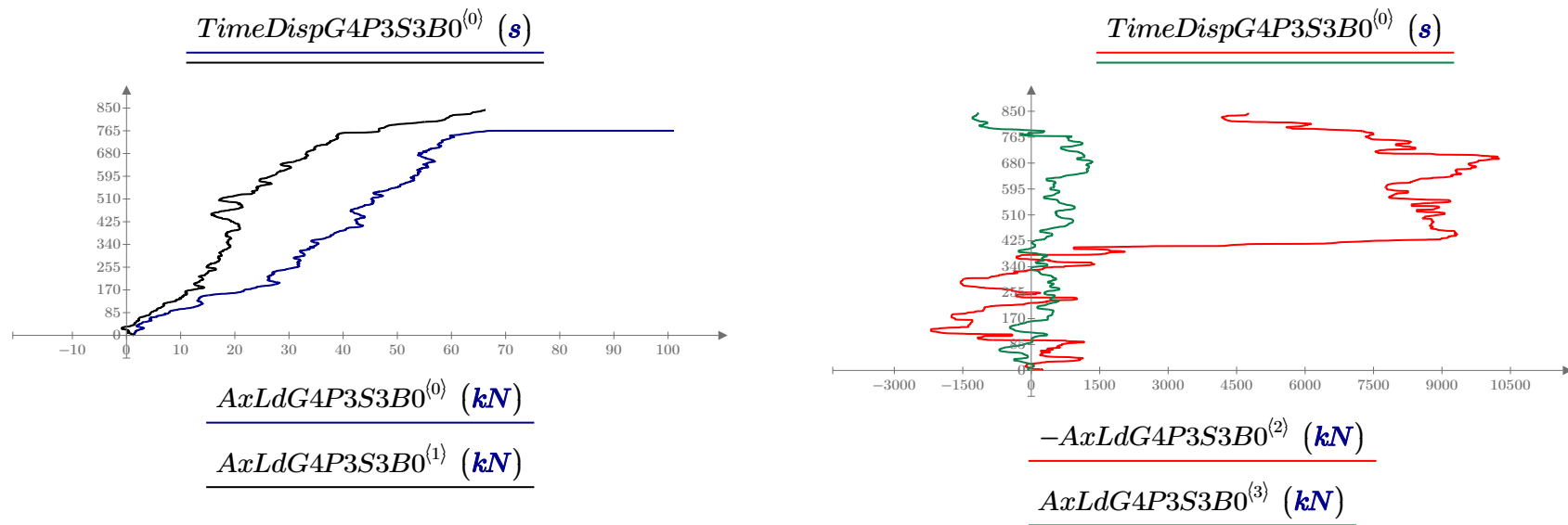


Fig F 2. Axial Load time history for pile group 4P3S3B0

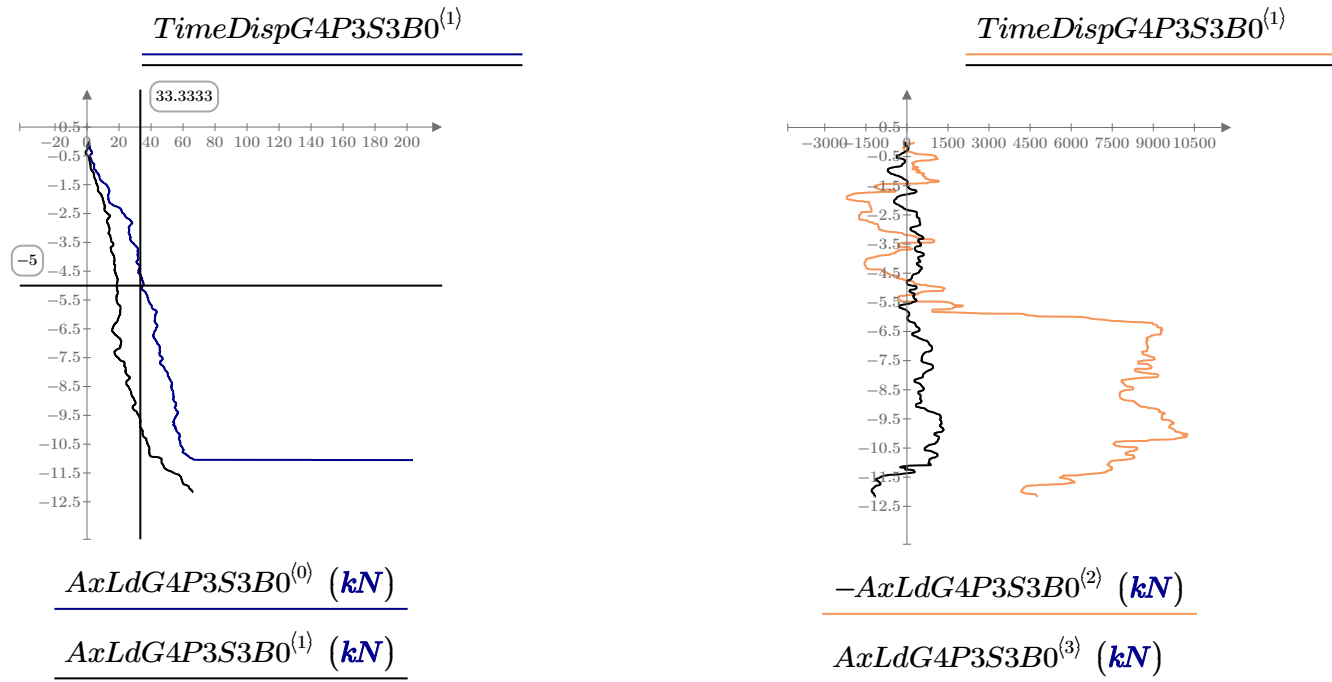


Fig F 3. Axial Load -displacement for pile group 4P3S3B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SCplotQP (AxLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
  ||
  || augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  ||
  || else
  ||
  || augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  ||
  QP1 ← if PileNum = 0
  ||
  || augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  ||
  || else
  ||
  || augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  ||
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near"))
  ||
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near"))
  ||
  combined ← if PileNum = 0
  ||
  || stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  ||
  || else
  ||
  || stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  ||
  combined

```

$$Qdist4P3S3B0 := SGplotQP(AxLdG4P3S3B0, TimeDispG4P3S3B0, 3) = \begin{bmatrix} 23.0565 & 35.0799 & 47.1032 & 55.7318 \\ 12.9775 & 18.4885 & 19.3774 & 34.3105 \\ 12.9775 & 18.4885 & 19.3774 & 34.3105 \\ 1714.4094 & -1319.4757 & -8641.9413 & -10061.9969 \\ 1714.4094 & -1319.4757 & -8641.9413 & -10061.9969 \\ 358.7574 & 352.4044 & 525.0564 & 1004.1471 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{selfac_{0,0}} \quad \begin{array}{l} SG \text{ embedment depth in prototype scale. Here, colm 0-4 represents} \\ P0 \text{ to P4. Row 0 to 5 represents depth to strain SG 1 to 4} \end{array}$$

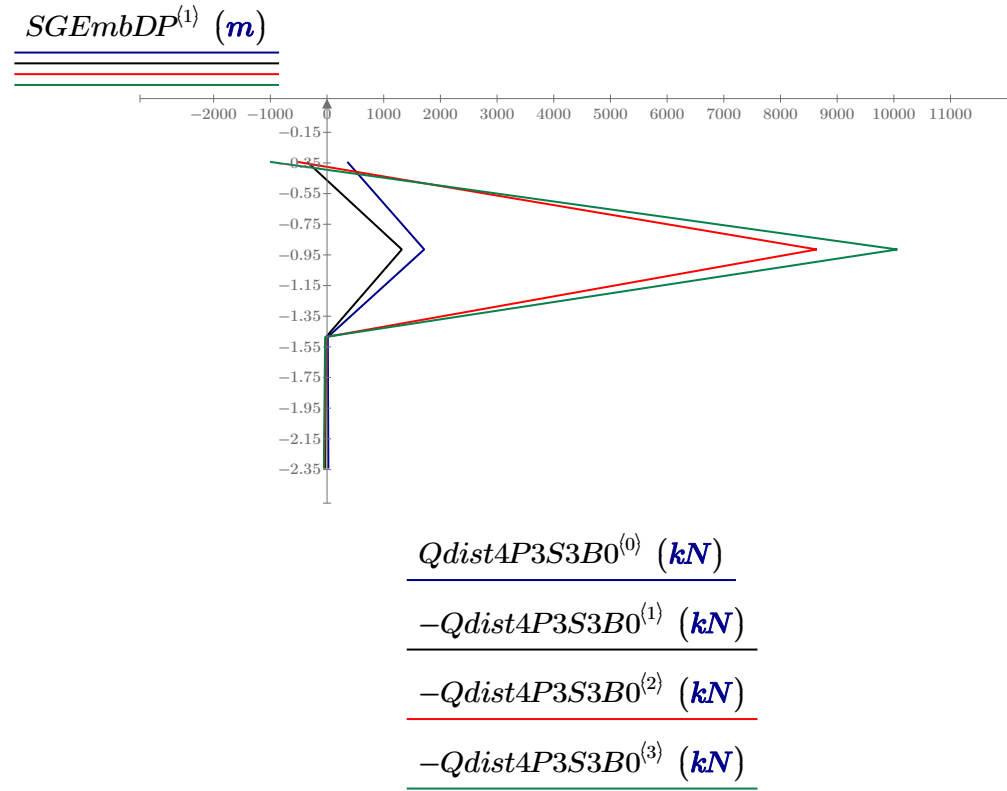


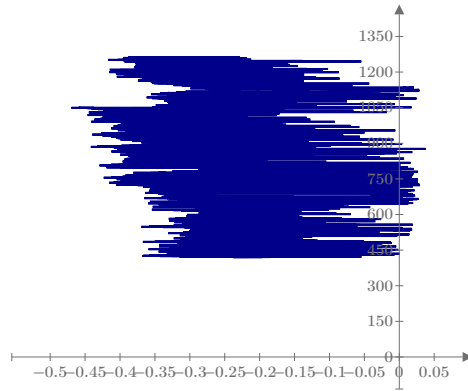
Fig F 4. Axial Load -displacement for pile group 4P3S3B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

2.3.3 Bending Moment vs Time

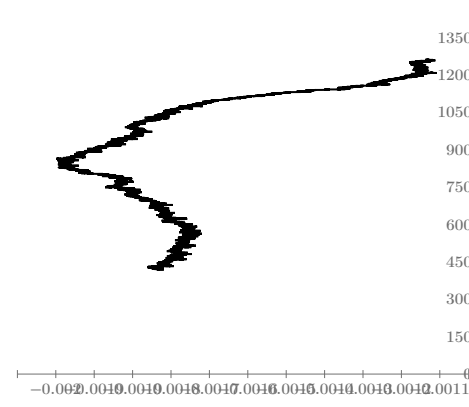
$BM1G4P3S3B0 := ConvLd(G4P3S3B0HBM, 4, CFBM, 999, 2)$

$BM2G4P3S3B0 := ConvLd(G4P3S3B0HBM, 2, CFBM, 999, 3)$



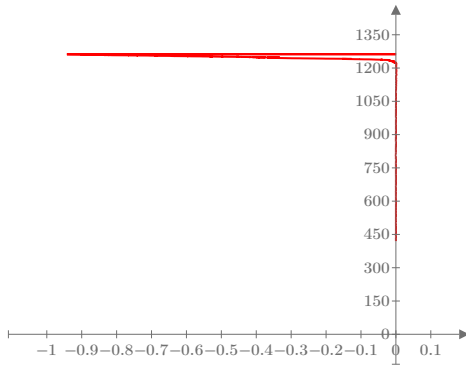
$G4P3S3B0HBM^{(1)}$

$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



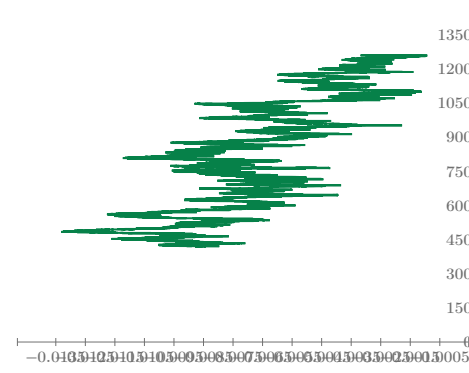
$G4P3S3B0HBM^{(2)}$

$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G4P3S3B0HBM^{(3)}$

$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G4P3S3B0HBM^{(4)}$

$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

Fig F 5. Raw Data Bending Moment 1 for pile group 4P3S3B0

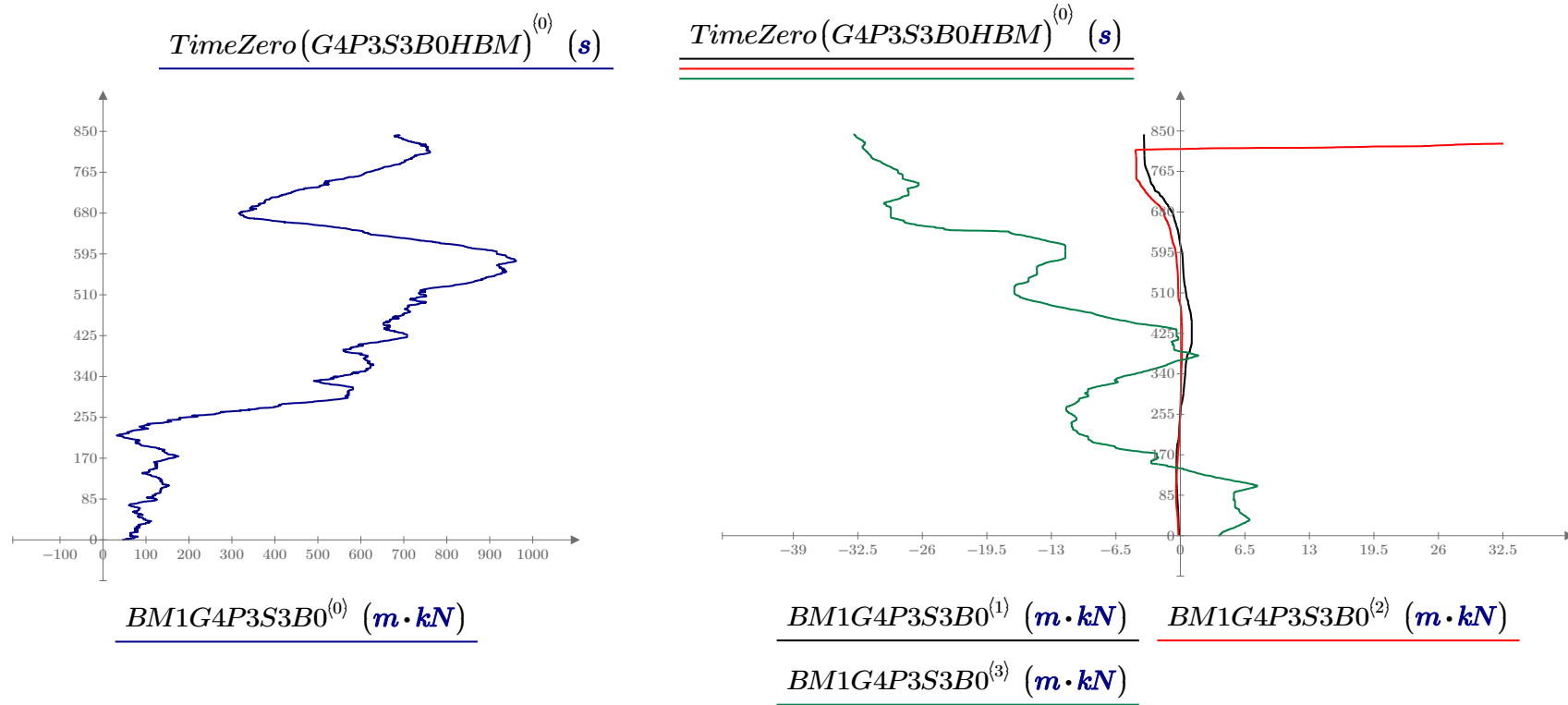


Fig F 6. Bending Moment 1 time history for pile group 4P3S3B0

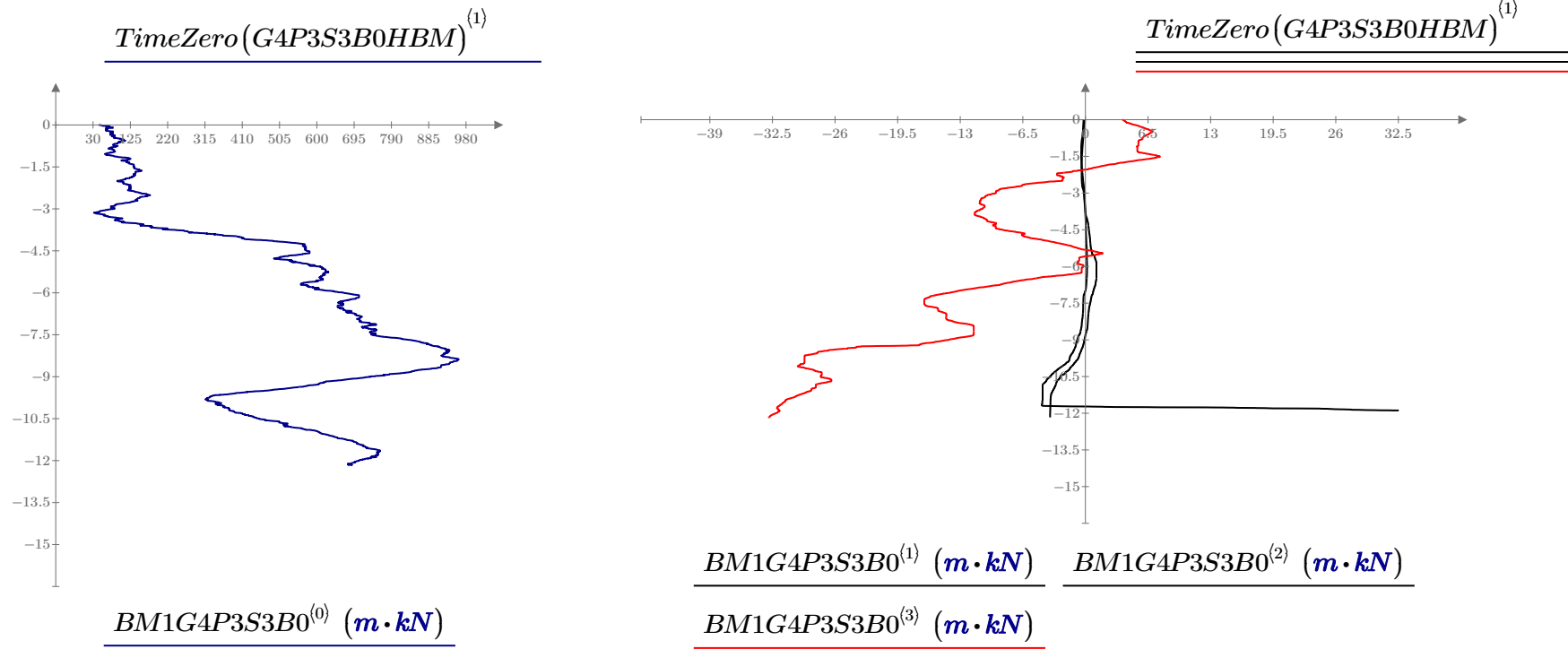


Fig F 7. Bending Moment 1 - displacement for pile group 4P3S3B0

$$BMM_{axdist4P3S3B0} := SGplotQP(BM1G4P3S3B0, TimeDispG4P3S3B0, 3) = \begin{bmatrix} 170.2746 & 581.4408 & 739.355 & 346.6618 \\ -0.3734 & 0.5033 & 0.5033 & -1.2257 \\ -0.3734 & 0.5033 & 0.5033 & -1.2257 \\ -0.2349 & 0.0909 & -0.2198 & -2.1068 \\ -0.2349 & 0.0909 & -0.2198 & -2.1068 \\ -2.4489 & -3.3533 & -16.7324 & -29.608 \end{bmatrix} m \cdot kN$$

Appendix F
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

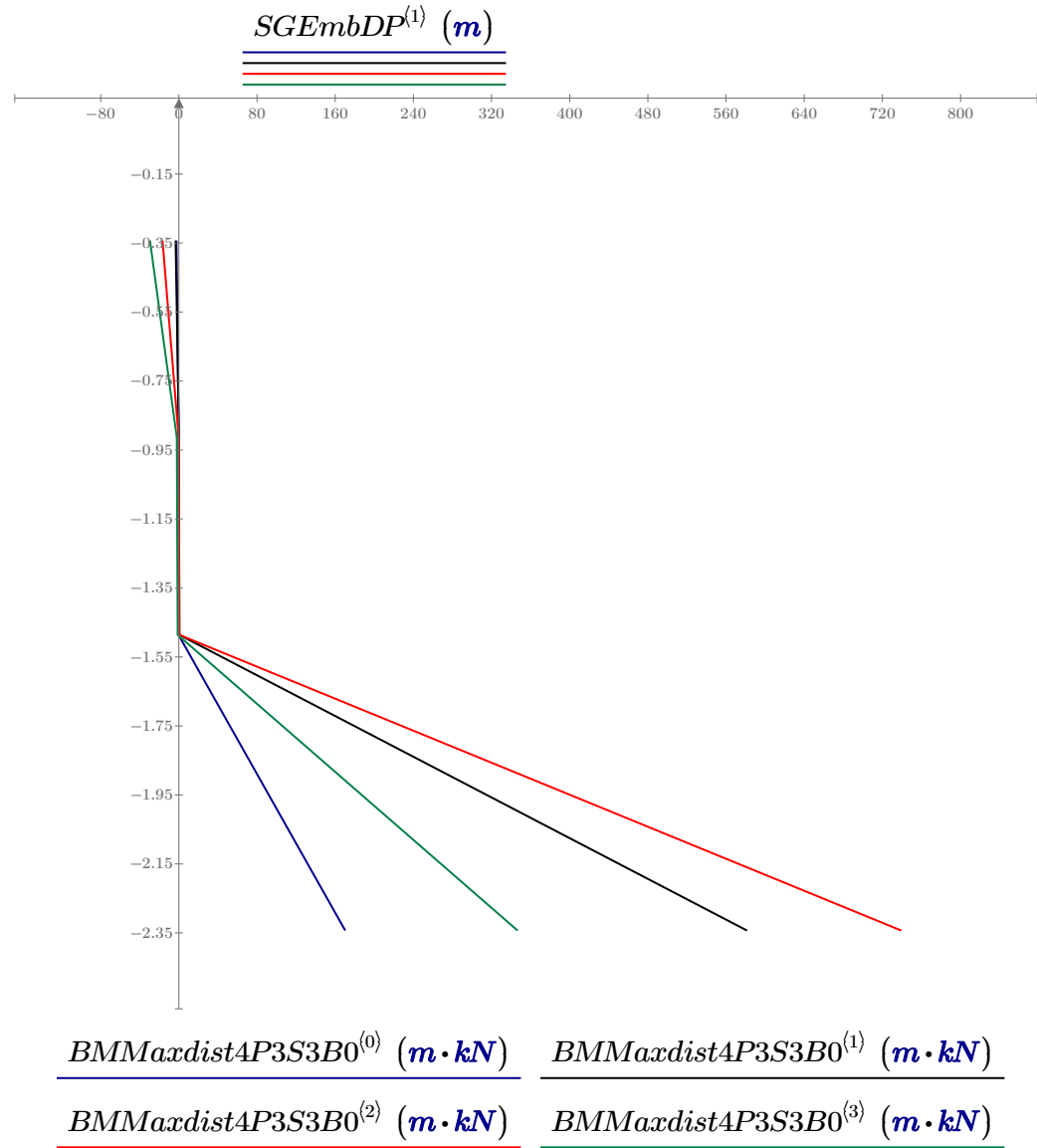
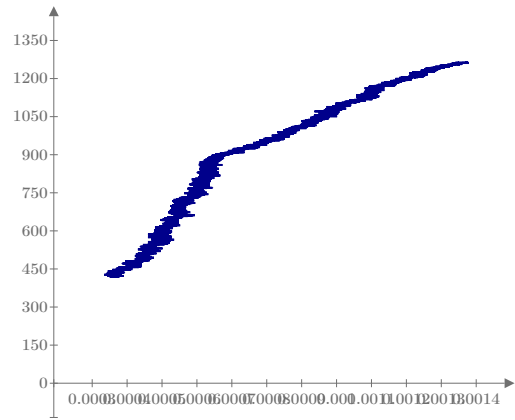


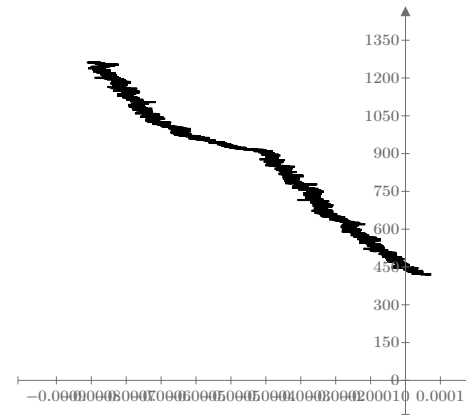
Fig F 8. Bending Moment 1 - depth for pile group 4P3S3B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group



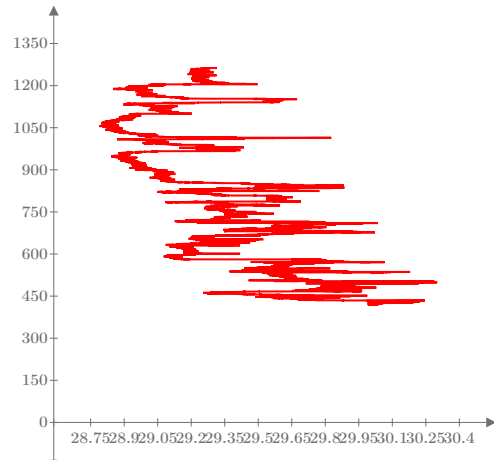
$G4P3S3B0HBM^{(5)}$

$$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



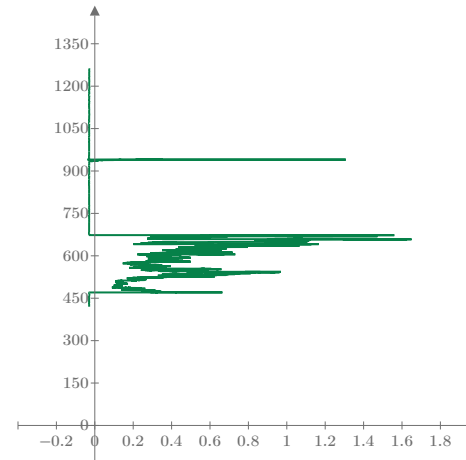
$G4P3S3B0HBM^{(6)}$

$$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



$G4P3S3B0HBM^{(7)} \left(\frac{mV}{V} \right)$

$$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$



$G4P3S3B0HBM^{(8)}$

$$G4P3S3B0HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$$

Fig F 9. Raw Data Bending Moment 2 for pile group 4P3S3B0

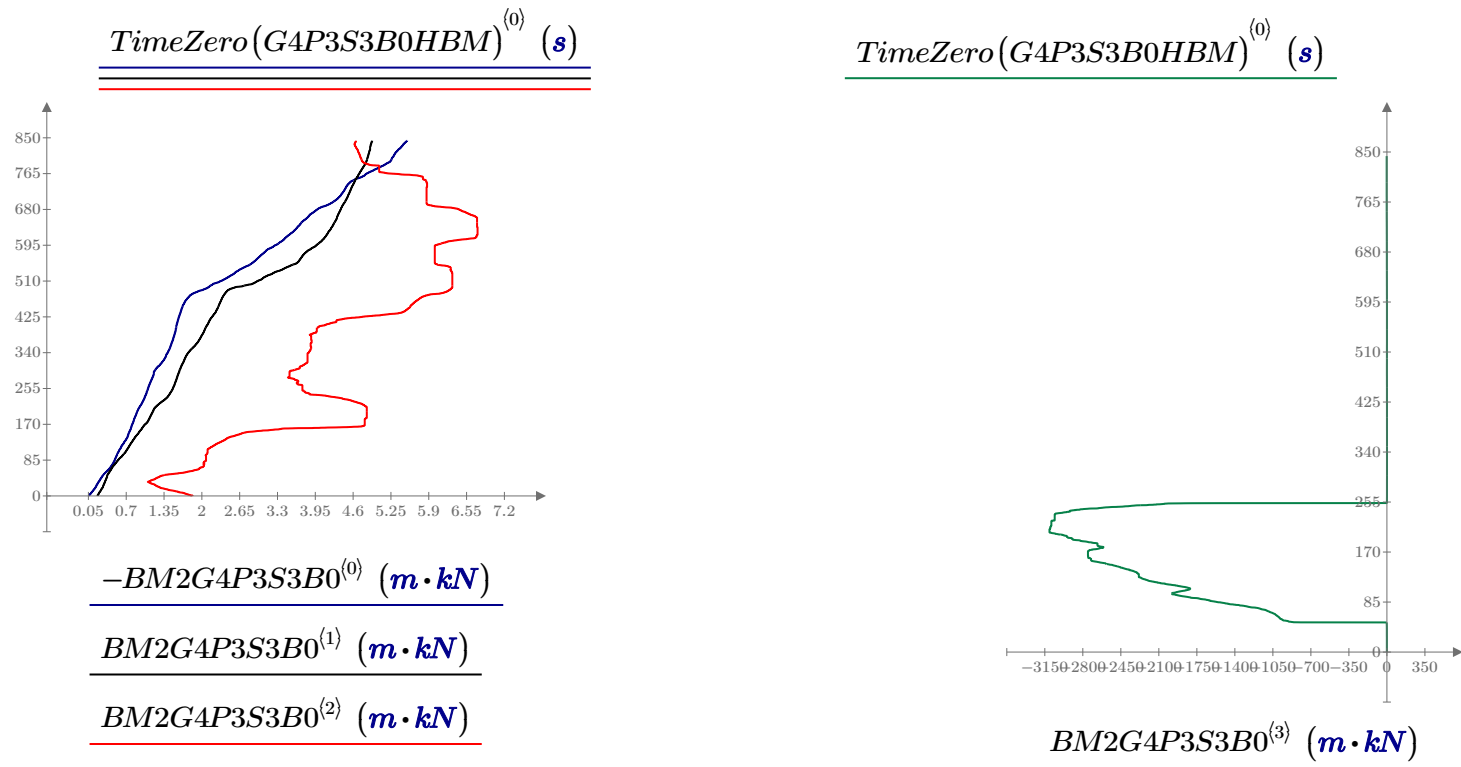


Fig F 10. Bending Moment 2 time history for pile group 4P3S3B0

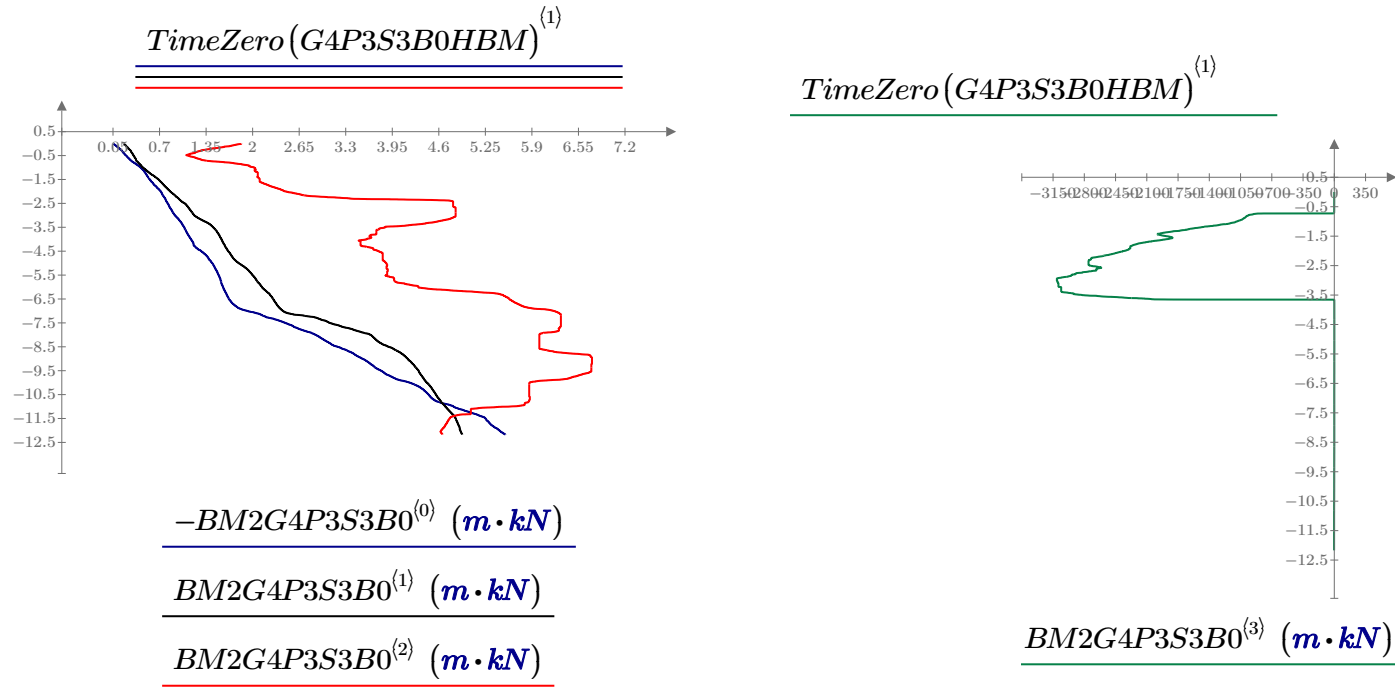


Fig F 11. Bending Moment 2 - displacement for pile group 4P3S3B0

$$BMMindist4P3S3B0 := SGplotQP(BM2G4P3S3B0, TimeDispG4P3S3B0, 3) = \begin{bmatrix} -0.8152 & -1.4376 & -2.4544 & -4.1901 \\ 1.0526 & 1.8032 & 3.0714 & 4.4346 \\ 1.0526 & 1.8032 & 3.0714 & 4.4346 \\ 4.7995 & 3.8697 & 6.3049 & 5.871 \\ 4.7995 & 3.8697 & 6.3049 & 5.871 \\ -2739.2149 & 0.6091 & 0.0483 & -0.8509 \end{bmatrix} m \cdot kN$$

Appendix F

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

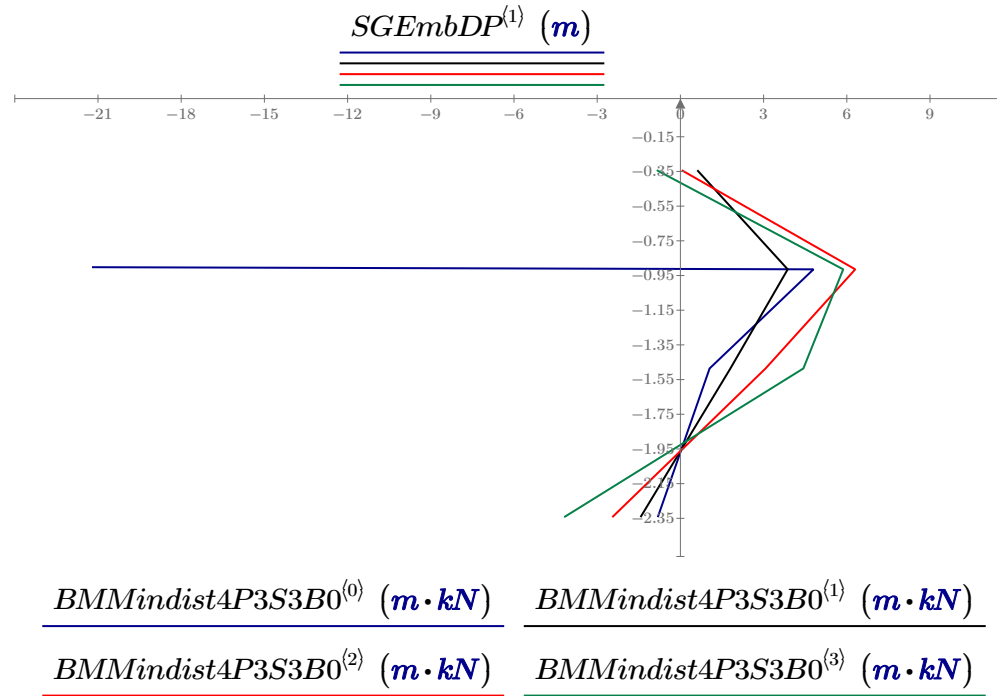


Fig F 12. Bending Moment 2 - depth for pile group 4P3S3B0

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) := || TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
                             || LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
                             || LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
                             || for i ∈ 0, 1..rows(LVDTRawData) - 1
                             ||   k_i ← (TimeLVDT_i - TimeLVDT_0)
                             ||   q_i ← -(LVDT1_i - LVDT1_0) · 2 · Nscalescifac0,0
                             ||   m_i ← -(LVDT2_i - LVDT2_0) · 2 · Nscalescifac0,0
                             ||   n_i ← -(TimeLVDT_i - TimeLVDT_0) · CmpRate · Nscalescifac0,0
                             || augment(k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-3P3B0G.xlsx"}, \text{"Sheet1 (2)!A2:C845"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

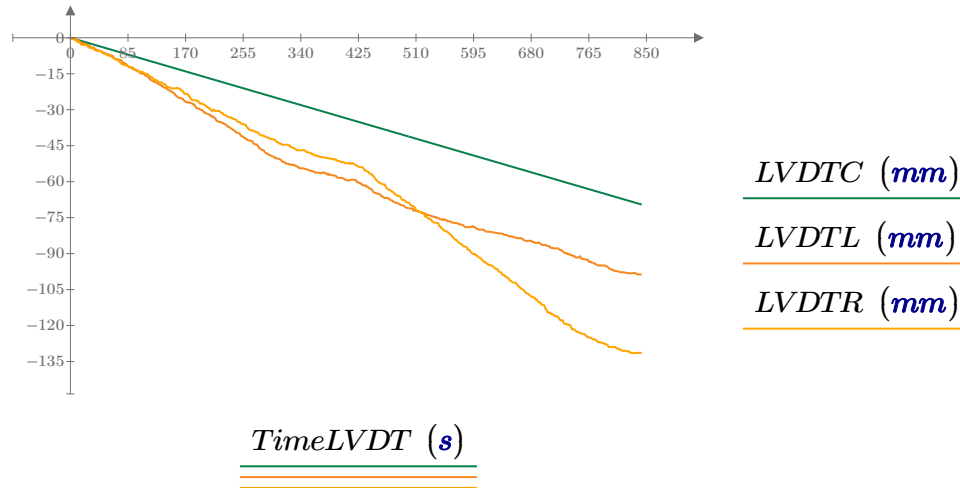


Fig F 13. LVDT displacements time history for pile group 4P3S3B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S3B0 Helix Pile Group

Function for determining the tilting of the plate

$$\begin{aligned}
 \text{Tilt}(\text{SpacingDCDLR}, \text{SpacingDLDR}) := & \begin{array}{l} k \leftarrow (\text{SpacingDCDLR}) \cdot \text{mm} \cdot \text{Nscale}^{sclfac}_{0,0} \\ q \leftarrow (\text{SpacingDLDR}) \cdot \text{mm} \cdot \text{Nscale}^{sclfac}_{0,0} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{LVDTRawData}) - 1 \\ \quad \begin{array}{l} m_i \leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ n_i \leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ l_i \leftarrow \frac{(LVDTR_i - LVDTL_i)}{q} \end{array} \\ \text{augment}(m, n, l) \end{array}
 \end{aligned}$$

$$\text{Rot4P3S3B0} := \text{augment}\left(\text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(0)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(1)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(2)}, 99\right)\right)$$

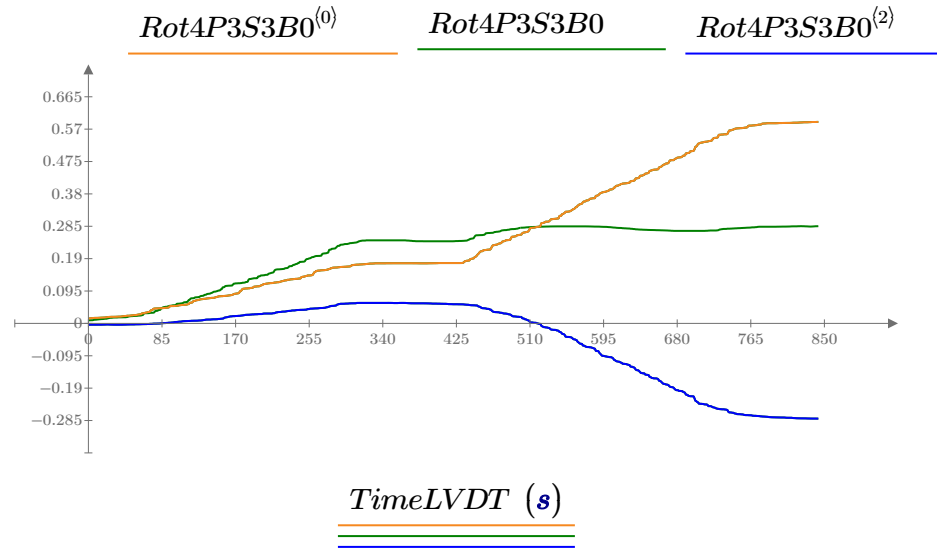


Fig F 14. LVDT rotations time history for pile group 4P3S3B0

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

1. Introduction

The series of sheets in Appendix G contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P0S2B10 Smooth Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

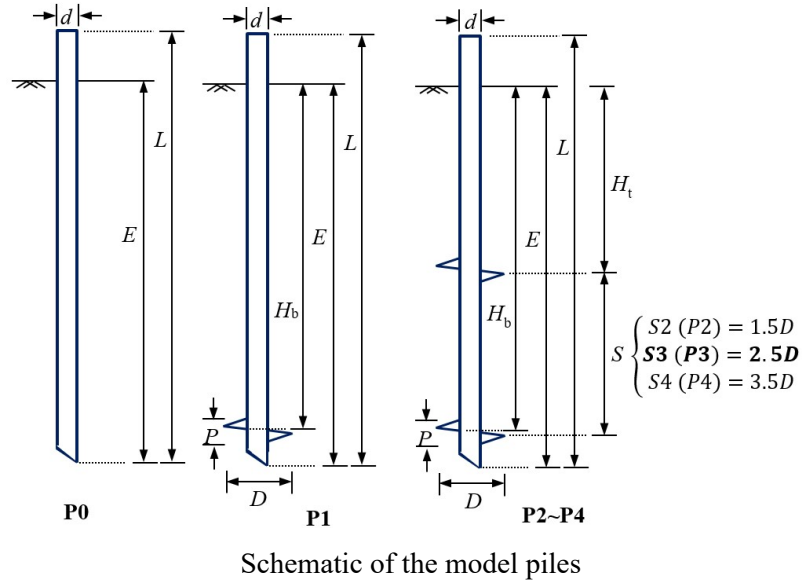
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{matrix} \begin{bmatrix} 1671.552 & 1617.456 & 1844.258 & 2163.61 & 2039.975 & 2126.783 \\ 1603.236 & 1910.523 & 2019.937 & 1886.937 & 1661.325 & 2108.164 \\ 1504.508 & 1572.619 & 1542.688 & 1762.074 & 1214.313 & 1879.545 \\ 0 & 0 & 1795.623 & 1568.123 & 1863.2 & 2113.142 \\ 0 & 0 & 1944.587 & 1539.661 & 1643.1 & 2098.613 \\ 0 & 0 & 1581.341 & 1519.014 & 1500.427 & 1957.742 \\ 0 & 0 & 1849.034 & 1644.78 & 1735.597 & 2080.164 \\ 0 & 0 & 1988.834 & 1577.768 & 1474.675 & 2136.155 \\ 0 & 0 & 1624.085 & 1561.886 & 1464.268 & 2031.605 \\ 2330.106 & 1805.307 & 2131.799 & 1656.108 & 1698.213 & 2226.545 \\ 1793.588 & 1802.381 & 2125.35 & 1710.166 & 1750.884 & 2327.124 \\ 1888.54 & 1670.165 & 1706.711 & 1655.981 & 1813.877 & 2437.397 \end{bmatrix} \\ \frac{N \cdot m}{mV} \\ V \end{matrix}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

```

ConvLd(RawdataHBM, PileNum, CF, smthn, LdType) :=
  RawDataSG ← if LdType = 1
    || -submatrix(RawdataHBM, 0, rows(RawdataHBM) - 1, 9, 12) || •  $\frac{mV}{V}$ 
    || else if LdType = 2
    || -submatrix(RawdataHBM, 0, rows(RawdataHBM) - 1, 1, 4) || •  $\frac{mV}{V}$ 
    || else
    || -submatrix(RawdataHBM, 0, rows(RawdataHBM) - 1, 5, 8) || •  $\frac{mV}{V}$ 
  for i ∈ 0, 1..rows(RawDataSG) - 1
    for j ∈ 0, 1..cols(RawDataSG) - 1
      ||  $q_{i,j} \leftarrow RawDataSG_{i,j} - RawDataSG_{0,j}$  ||
    SG1i,0 ← if LdType = 1
      ||  $\left( q_{i,0} \cdot \text{mean}(\text{submatrix}(CF, 0, 2, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,1}} \right)$  ||
      || else
      ||  $\left( q_{i,0} \cdot \text{mean}(\text{submatrix}(CF, 0, 2, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,2}} \right)$  ||
    SG2i,1 ← if LdType = 1
      ||  $\left( q_{i,1} \cdot \text{mean}(\text{submatrix}(CF, 3, 5, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,1}} \right)$  ||
      || else
      ||  $\left( q_{i,1} \cdot \text{mean}(\text{submatrix}(CF, 3, 5, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,2}} \right)$  ||
    SG3i,2 ← if LdType = 1
      ||  $\left( q_{i,2} \cdot \text{mean}(\text{submatrix}(CF, 6, 8, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,1}} \right)$  ||
      || else
      ||  $\left( q_{i,2} \cdot \text{mean}(\text{submatrix}(CF, 6, 8, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,2}} \right)$  ||
    SG4i,3 ← if LdType = 1
      ||  $\left( q_{i,3} \cdot \text{mean}(\text{submatrix}(CF, 9, 11, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,1}} \right)$  ||
      || else
      ||  $\left( q_{i,3} \cdot \text{mean}(\text{submatrix}(CF, 9, 11, PileNum, PileNum)) \cdot Nscale^{sclfac_{0,2}} \right)$  ||
  augment(medsmooth(SG1(0), smthn), medsmooth(SG2(1), smthn), medsmooth(SG3(2), smthn), medsmooth(SG4(3), smthn))

```

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

Function for determining the time and displacement

$$TimeZero(RawdataHBM) := \left\| \begin{array}{l} TimeP \leftarrow \text{submatrix}(RawdataHBM, 0, \text{rows}(RawdataHBM) - 1, 0, 0) \text{ } s \\ \text{for } i \in 0, 1 \dots \text{rows}(TimeP) - 1 \\ \quad k_i \leftarrow (TimeP_i - TimeP_0) \\ \quad q_i \leftarrow -(TimeP_i - TimeP_0) \cdot \frac{CmpRate}{d} \cdot 100 \\ \text{augment}(k, q) \end{array} \right\|$$

There were two strain gages placed within the P0 pile. The following sub sections provides the details on the load distributions:

$G4P0S2B10HBM := \text{READExcel}(\text{".\2P0B10G.xlsx"}, \text{"Sheet1 (3)!A33:M6203"})$

$TimeDispG4P0S2B10 := TimeZero(G4P0S2B10HBM)$

$AxLdG4P0S2B10 := ConvLd(G4P0S2B10HBM, 0, CFAxl, 11, 1)$

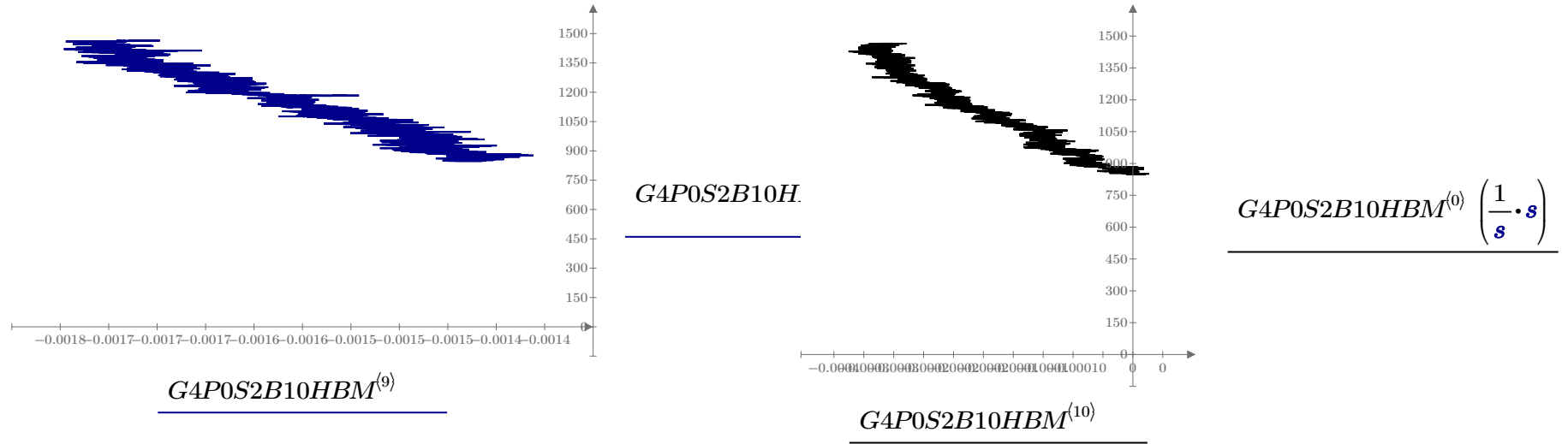


Fig G 1. Rawdata axial load time history for pile group 4P0S2B10

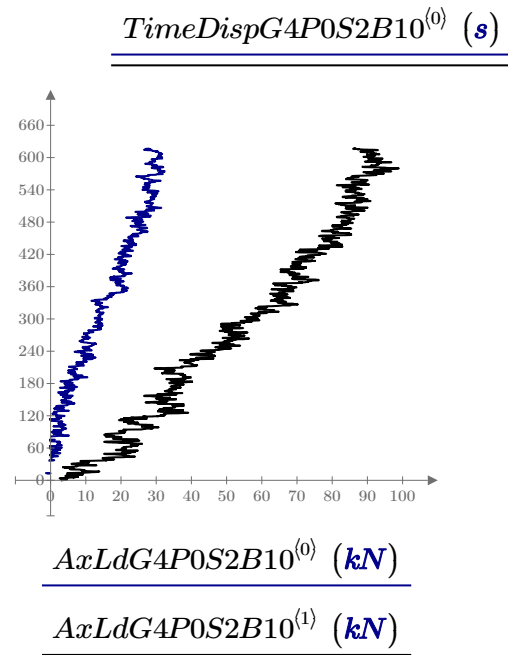


Fig G 2. Axial Load time history for pile group 4P0S2B10

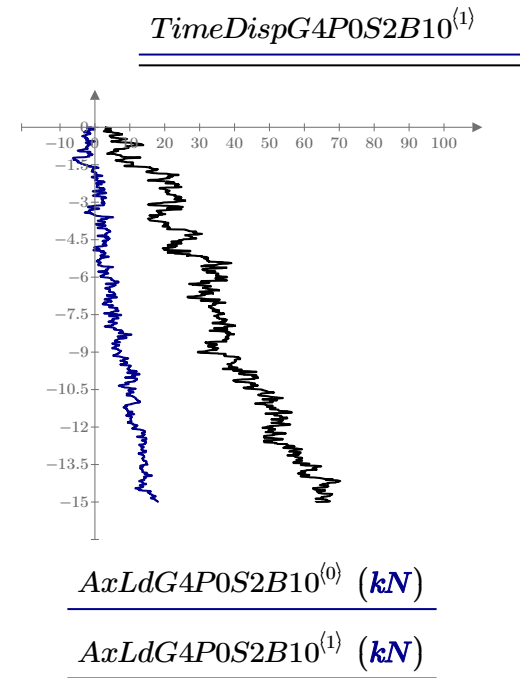


Fig G 3. Axial Load -displacement for pile group 4P0S2B10

Appendix G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SGplotQP (AxLdG4P3S2B0, TimeDispG4P3S2B0, PileNum) :=
  QP0 ← if PileNum = 0
    augment (lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-15, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-20, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"))
  else
    augment (lookup (-2.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(0), "near"))
  QP1 ← if PileNum = 0
    augment (lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-15, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-20, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"))
  else
    augment (lookup (-2.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(1), "near"))
  QP2 ← augment (lookup (-2.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(2), "near"), lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(2), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(2), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(2), "near"))
  QP3 ← augment (lookup (-2.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(3), "near"), lookup (-5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(3), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(3), "near"), lookup (-10, TimeDispG4P3S2B0(1), AxLdG4P3S2B0(3), "near"))
  combined ← if PileNum = 0
    stack (QP0, QP1, QP1, QP1, QP1, QP1)
  else
    stack (QP0, QP1, QP1, QP2, QP2, QP3)
  combined

```

$$Qdist4P0S2B0 := SGplotQP(AxLdG4P0S2B10, TimeDispG4P0S2B10, 0) = \begin{bmatrix} 1.6962 & 9.8689 & 17.8873 & 27.4478 \\ 23.5775 & 46.734 & 63.154 & 81.6792 \\ 23.5775 & 46.734 & 63.154 & 81.6792 \\ 23.5775 & 46.734 & 63.154 & 81.6792 \\ 23.5775 & 46.734 & 63.154 & 81.6792 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{sclfac}_{0,0}$$

SG embedment depth in prototype scale. Here, colm 0-4 represents P0 to P4. Row 0 to 5 represents depth to strain SG 1 to 4

Appendix G
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

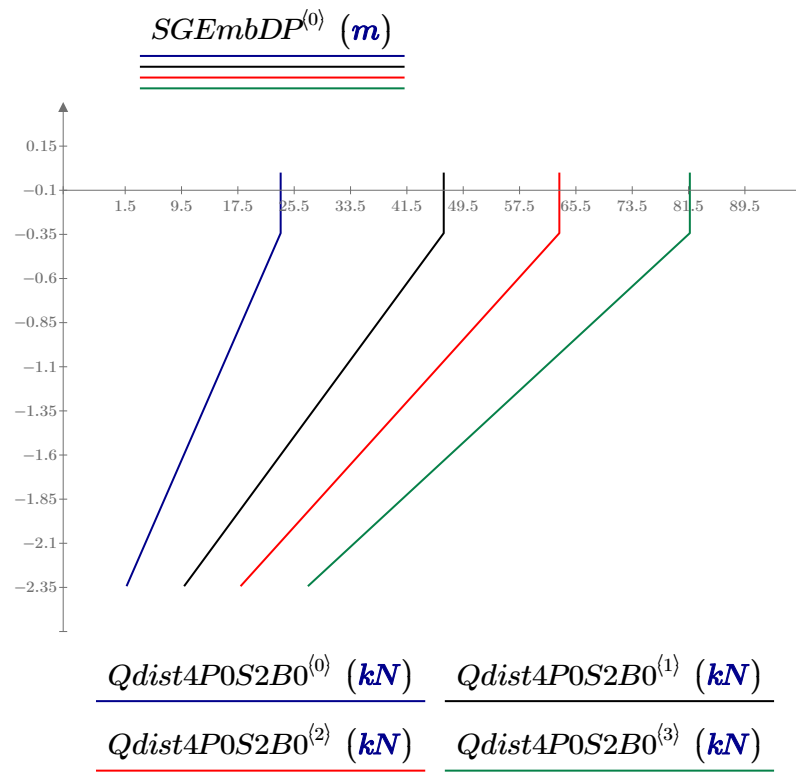
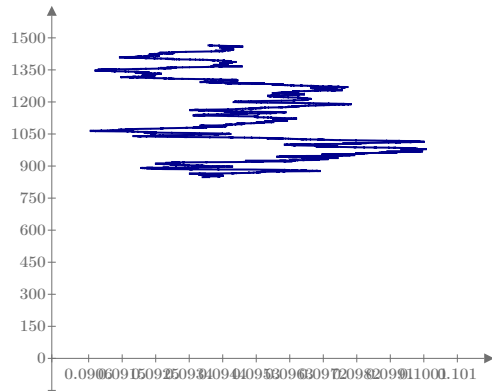


Fig G 4. Axial Load -depth for pile group 4P0S2B10

2.3.3 Bending Moment vs Time

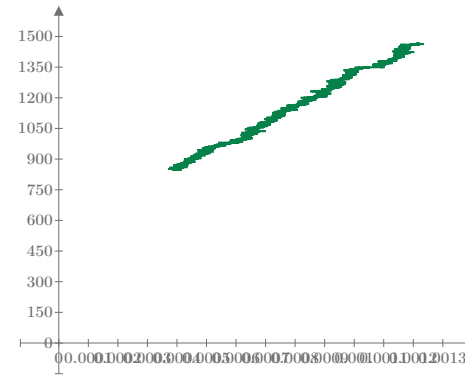
$BM1G4P0S2B10 := ConvLd(G4P0S2B10HBM, 1, CFBM, 111, 2)$

$BM2G4P0S2B10 := ConvLd(G4P0S2B10HBM, 0, CFBM, 77, 3)$



$G4P0S2B10HBM^{(1)}$

$G4P0S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G4P0S2B10HBM^{(4)}$

$G4P0S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

Fig G 5. Raw Data Bending Moment 1 for pile group 4P0S2B10

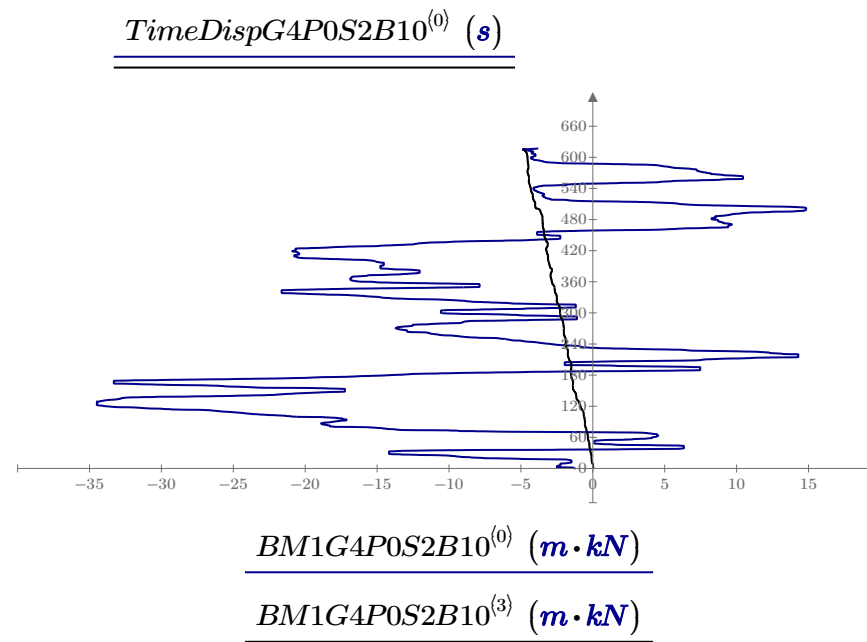
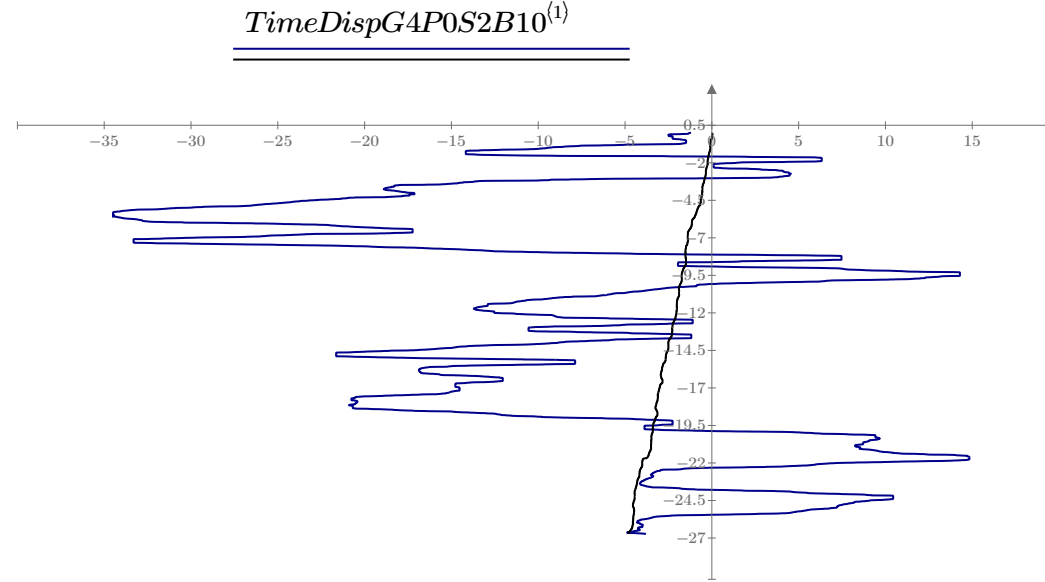


Fig G 6. Bending Moment 1 time history for pile group 4P0S2B10



$BM1G4P0S2B10^{(0)} \quad (m \cdot kN)$

$BM1G4P0S2B10^{(3)} \quad (m \cdot kN)$

Fig G 7. Bending Moment 1 - displacement for pile group 4P0S2B10

```
SGplotQP (AzLdG4P3S2B0, TimeDispG4P3S2B0, PileNum) :=
  QP0 ← if PileNum = 0
  | augment (lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-15, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-20, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"))
  | else
  | augment (lookup (-2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(0), "near"))
  QP1 ← if PileNum = 0
  | augment (lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-15, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-20, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"))
  | else
  | augment (lookup (-2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"))
  QP2 ← augment (lookup (-2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), "near"), lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(2), "near"))
  QP3 ← augment (lookup (-2.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-7.5, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"), lookup (-10, TimeDispG4P3S2B0(1), AzLdG4P3S2B0(3), "near"))
  combined ← if PileNum = 0
  | stack (QP0, QP1, QP1, QP1, QP1, QP1)
  | else
  | stack (QP0, QP1, QP1, QP2, QP2, QP3)
  combined
```

$$BMM_{axdist4P0S2B10} := SGplotQP (BM1G4P0S2B10, TimeDispG4P0S2B10, 0) = \begin{bmatrix} -30.4725 & 2.3568 & -17.2994 & 5.7224 \\ -0.8043 & -1.7798 & -2.6526 & -3.4227 \\ -0.8043 & -1.7798 & -2.6526 & -3.4227 \\ -0.8043 & -1.7798 & -2.6526 & -3.4227 \\ -0.8043 & -1.7798 & -2.6526 & -3.4227 \\ -0.8043 & -1.7798 & -2.6526 & -3.4227 \end{bmatrix} m \cdot kN$$

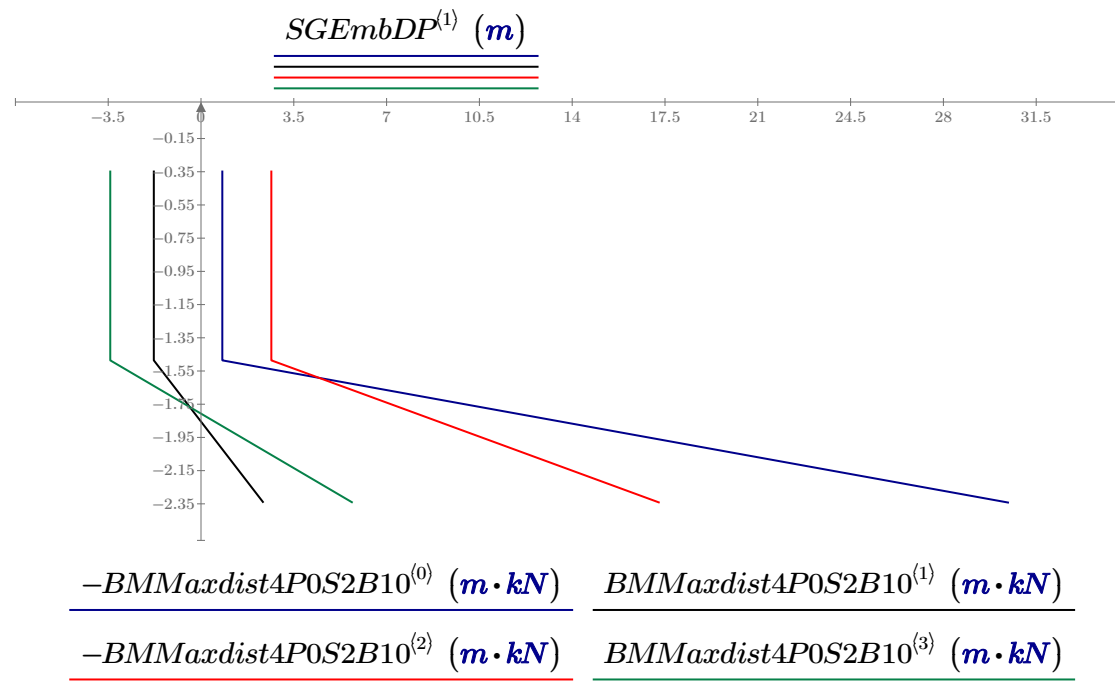


Fig G 8. Bending Moment 1 - depth for pile group 4P0S2B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

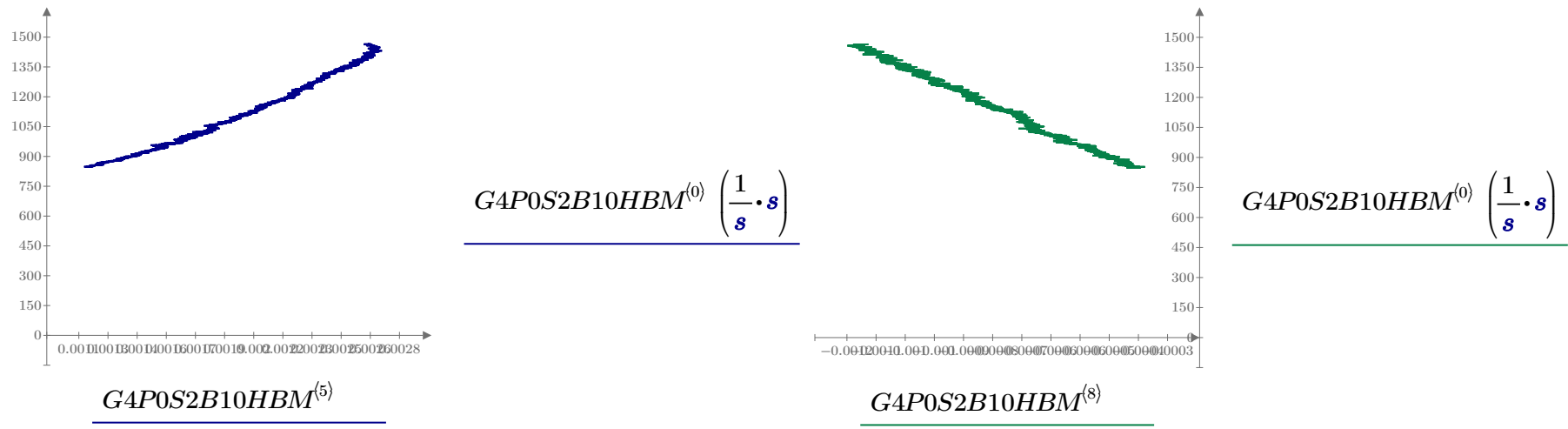


Fig G 9. Raw Data Bending Moment 2 for pile group 4P0S2B10

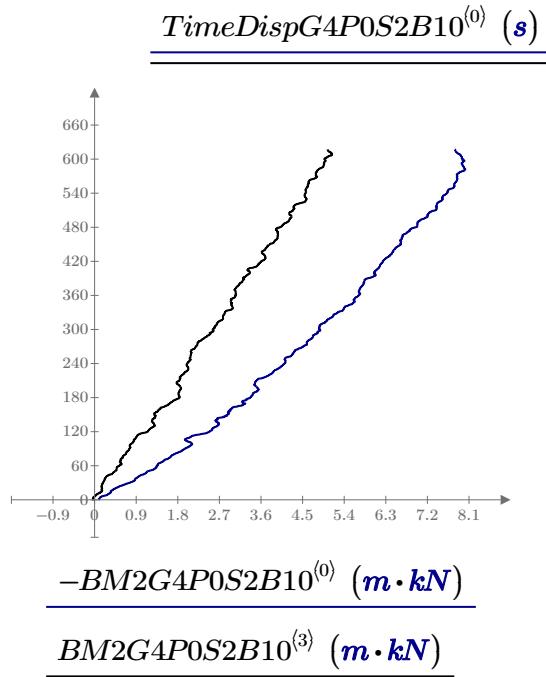


Fig G 10. Bending Moment 2 time history for pile group 4P0S2B10

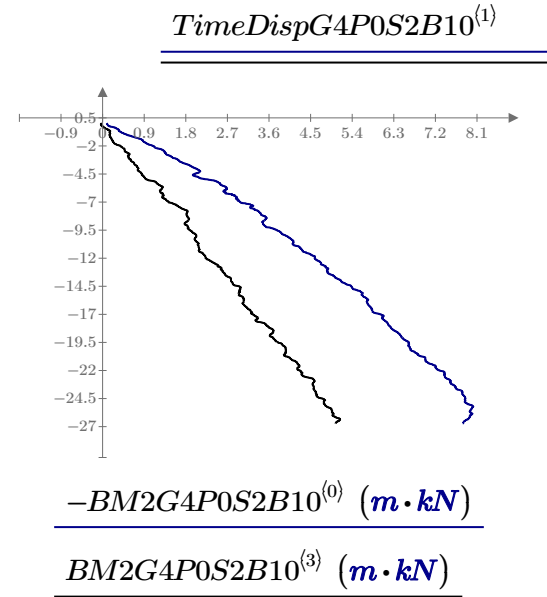


Fig G 11. Bending Moment 2 - displacement for pile group 4P0S2B10

$$BMMindist4P0S2B10 := SGplotQP(BM2G4P0S2B10, TimeDispG4P0S2B10, 0) = \begin{bmatrix} -2.2935 & -3.9672 & -5.5866 & -6.6481 \\ 0.965 & 2.0274 & 2.9729 & 3.9574 \\ 0.965 & 2.0274 & 2.9729 & 3.9574 \\ 0.965 & 2.0274 & 2.9729 & 3.9574 \\ 0.965 & 2.0274 & 2.9729 & 3.9574 \end{bmatrix} m \cdot kN$$

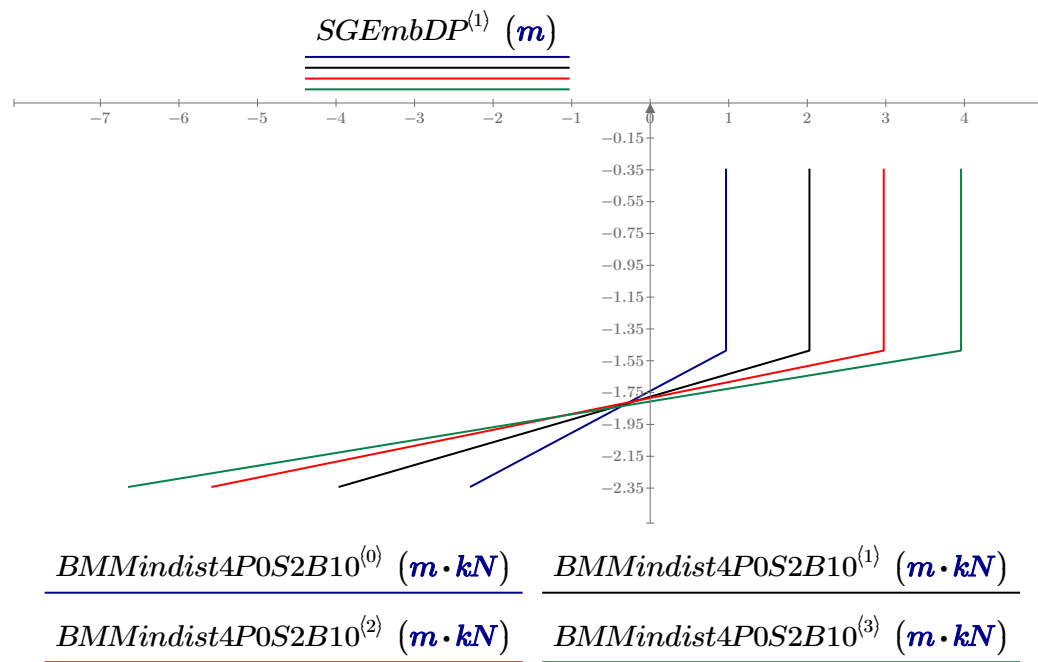


Fig G 12. Bending Moment 2 - depth for pile group 4P0S2B10

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) := || TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
                             || LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
                             || LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
                             || for i ∈ 0, 1..rows(LVDTRawData) - 1
                             ||   k_i ← (TimeLVDT_i - TimeLVDT_0)
                             ||   q_i ← -(LVDT1_i - LVDT1_0) • Nscalesclfac0,0
                             ||   m_i ← -(LVDT2_i - LVDT2_0) • Nscalesclfac0,0
                             ||   n_i ← -(TimeLVDT_i - TimeLVDT_0) • CmpRate • Nscalesclfac0,0
                             || augment(k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-2P0B10G.xlsx"}, \text{"Sheet1 (2)!A2:C622"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

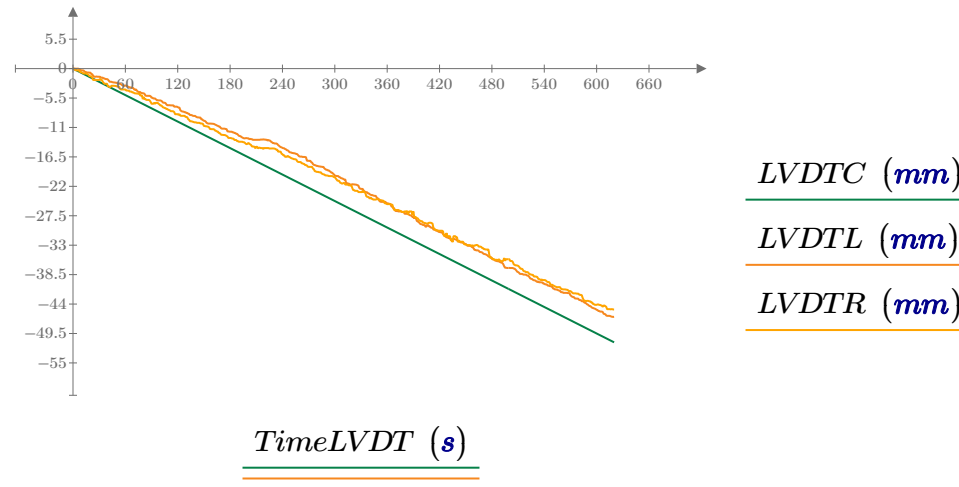


Fig G 13. LVDT displacements time history for pile group 4P0S2B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P0S2B10 Smooth Pile Group

Function for determining the tilting of the plate

$$Tilt(SpacingDCDLR, SpacingDLDR) := \begin{cases} k \leftarrow (SpacingDCDLR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ q \leftarrow (SpacingDLDR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ \text{for } i \in 0, 1 \dots \text{rows}(LVDTRawData) - 1 \\ \quad \left\| \begin{aligned} m_i &\leftarrow \frac{(LVDTC_i - LVDTR_i)}{k} \\ n_i &\leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ l_i &\leftarrow \frac{(LVDTR_i - LVDTL_i)}{q} \end{aligned} \right. \\ \text{augment}(m, n, l) \end{cases}$$

$$Rot4P0S2B10 := \text{augment} \left(\text{medsmooth} \left(Tilt(7.1, 7.8)^{(0)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(1)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(2)}, 99 \right) \right)$$

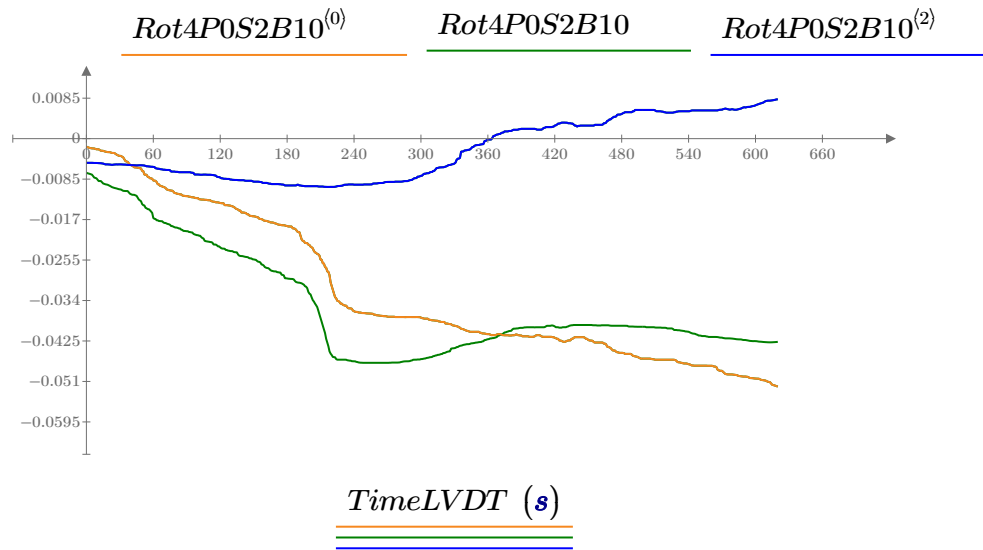


Fig G 14. LVDT rotations time history for pile group 4P0S2B10

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

1. Introduction

The series of sheets in Appendix H contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 2P3S2B20 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

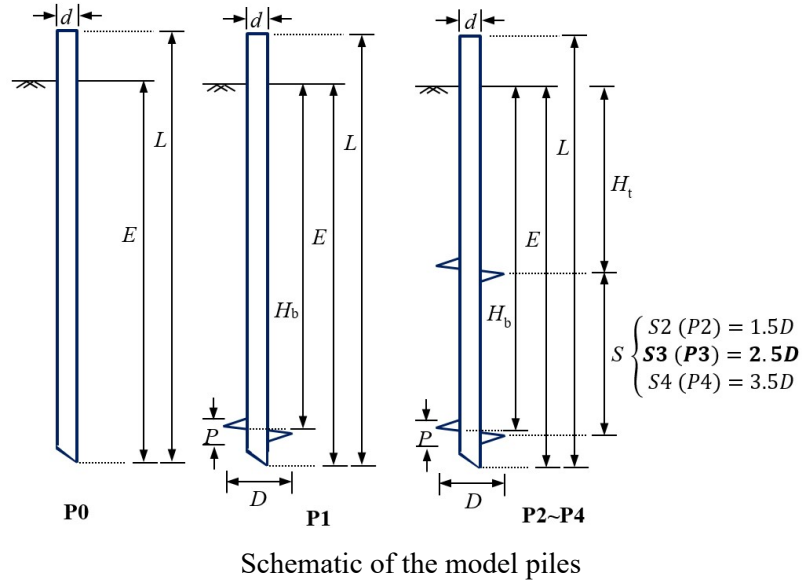
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := submatrix(RawDataCalib, 0, rows(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ k_{i,j} \leftarrow CmbLdAx_{i,0} \\ q_{i,j} \leftarrow CalibdataPile_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j}}{q_{i,j}} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 3-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg · g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) · $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ \quad \quad k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ \quad \quad l_{i,j} \leftarrow CmbMArm_{i,0} \\ \quad \quad q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ \quad \quad m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad \quad \quad 0 \\ \quad \quad \quad \text{else} \\ \quad \quad \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \frac{kN \cdot m}{V}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & \text{SG1}_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG2}_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG3}_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \\ & \text{SG4}_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ \text{else} \\ \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{cases} \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(\text{SG1}^{(0)}, \text{smthn}), \text{medsmooth}(\text{SG2}^{(1)}, \text{smthn}), \text{medsmooth}(\text{SG3}^{(2)}, \text{smthn}), \text{medsmooth}(\text{SG4}^{(3)}, \text{smthn}))
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{cases} \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \mathbf{8} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow -(\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{cases}
 \end{aligned}$$

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$G2P3S2B20HBM := \text{READExcel}(\text{".\2P3B20D.xlsx"}, \text{"Sheet1 (2)!A3:M5553"})$

$\text{TimeDisp}G2P3S2B20 := \text{TimeZero}(G2P3S2B20HBM)$

$\text{AxLd}G2P3S2B20 := \text{ConvLd}(G2P3S2B20HBM, 3, \text{CFAxl}, 111, 1)$

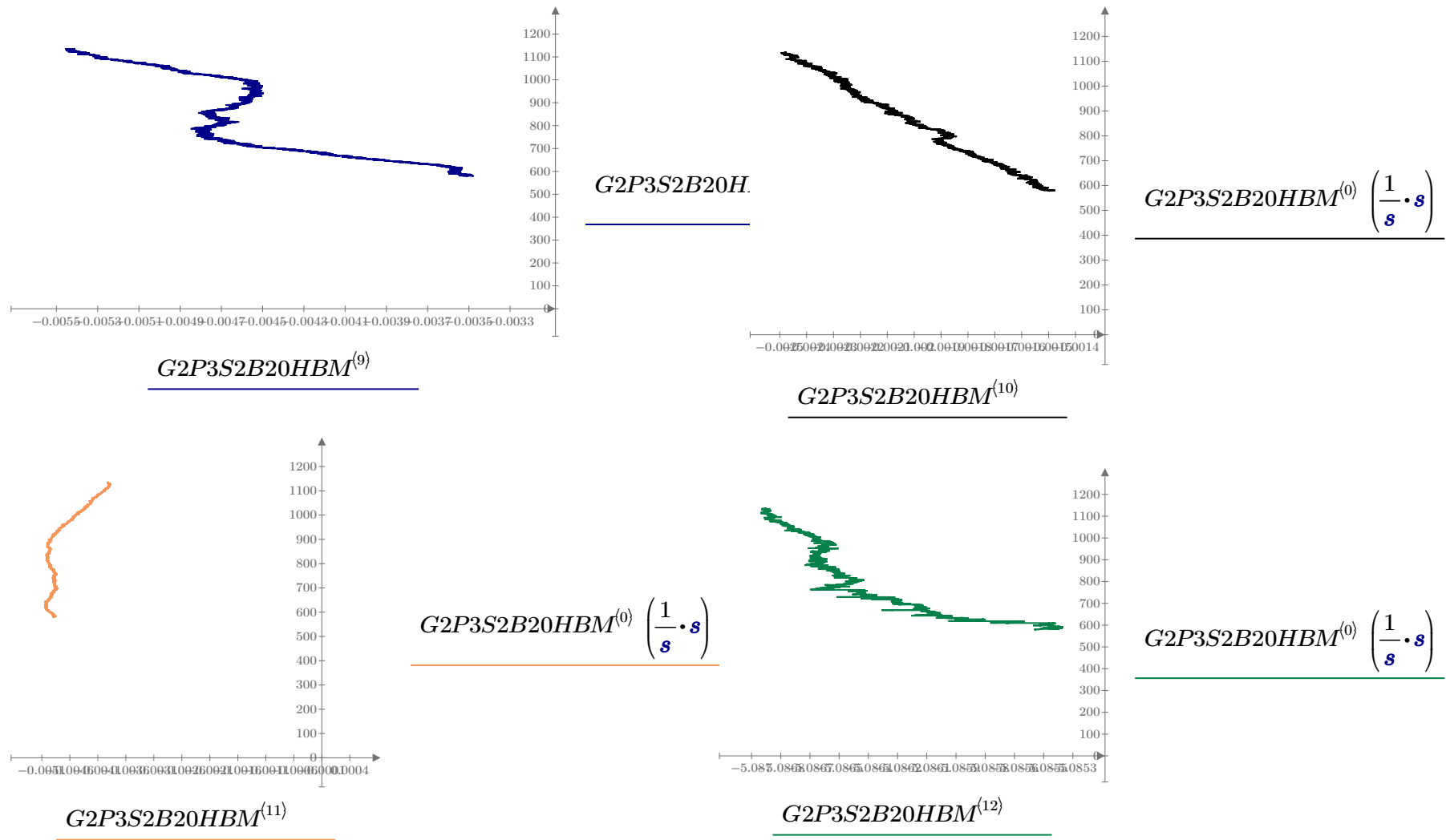


Fig H 1. Rawdata axial load time history for pile group 2P3S2B20

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

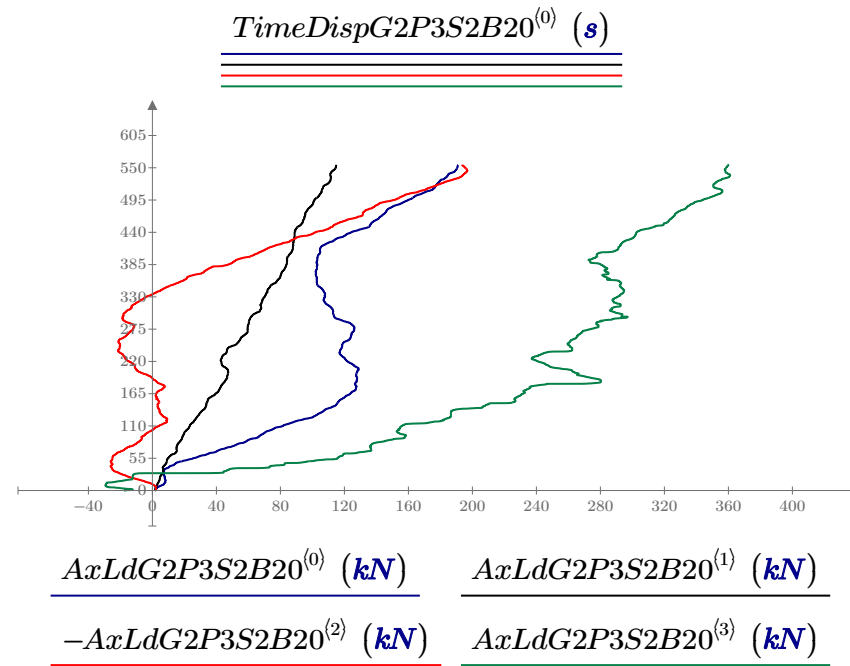


Fig H 2. Axial Load time history for pile group 2P3S2B20

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

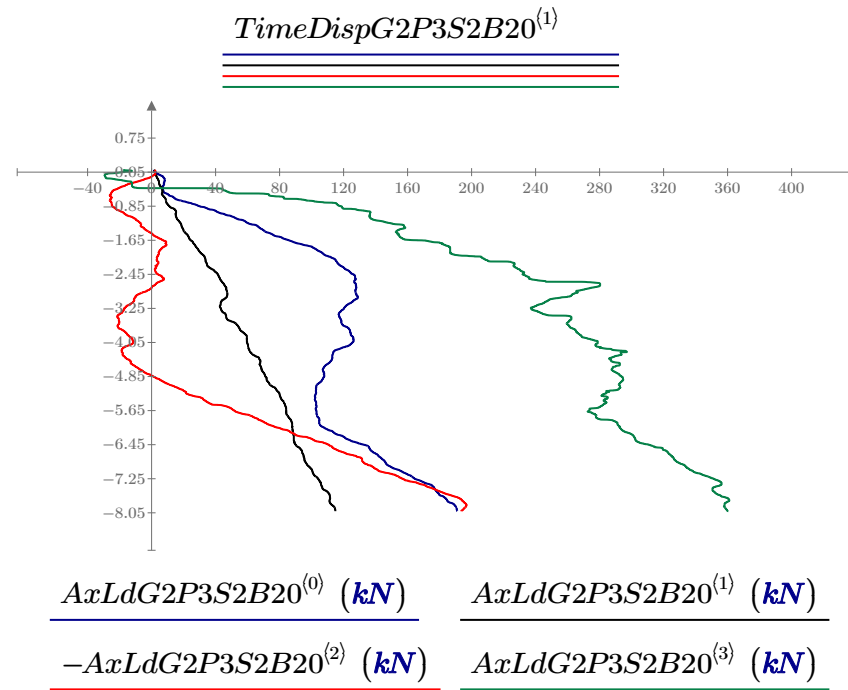


Fig H 3. Axial Load -displacement for pile group 2P3S2B20

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```

SGplotQP (AzLdGAP3S2B0 , TimeDispGAP3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
  │
  │ augment (lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-15 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-20 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ))
  │
  │ else
  │
  │ augment (lookup (-2.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-7.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(0) , "near" ))
  │
  QP1 ← if PileNum = 0
  │
  │ augment (lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-15 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-20 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ))
  │
  │ else
  │
  │ augment (lookup (-2.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-7.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(1) , "near" ))
  │
  QP2 ← augment (lookup (-2.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(2) , "near" ) , lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(2) , "near" ) , lookup (-7.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(2) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(2) , "near" ))
  QP3 ← augment (lookup (-2.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(3) , "near" ) , lookup (-5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(3) , "near" ) , lookup (-7.5 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(3) , "near" ) , lookup (-10 , TimeDispGAP3S2B0(1) , AzLdGAP3S2B0(3) , "near" ))
  combined ← if PileNum = 0
  │
  │ stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  │
  │ else
  │
  │ stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  │
  combined

```

$$QdistAP3S2B20 := SGplotQP (AxLdG2P3S2B20 , TimeDispG2P3S2B20 , 3) = \begin{bmatrix} 127.1646 & 104.8153 & 177.2383 & 191.0298 \\ 42.1326 & 73.4209 & 107.198 & 114.8423 \\ 42.1326 & 73.4209 & 107.198 & 114.8423 \\ -6.5348 & -8.8078 & -177.0098 & -193.489 \\ -6.5348 & -8.8078 & -177.0098 & -193.489 \\ 235.0636 & 292.6857 & 350.5552 & 360.1382 \end{bmatrix} \quad \textcolor{blue}{kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{sclfac}_{0,0} \quad \begin{array}{l} SG \text{ embedment depth in prototype scale. Here, colm 0-4 represents} \\ P0 \text{ to P4. Row 0 to 5 represents depth to strain SG 1 to 4} \end{array}$$

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

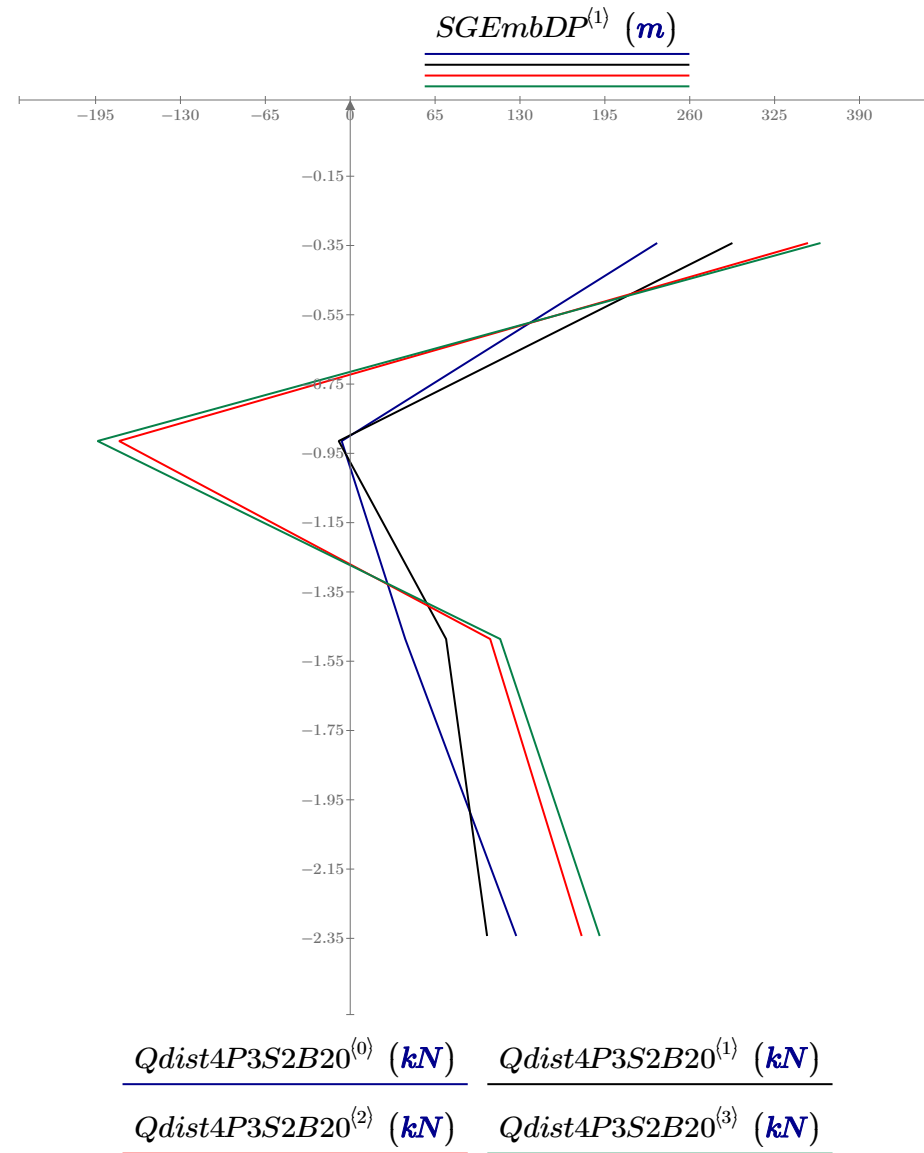
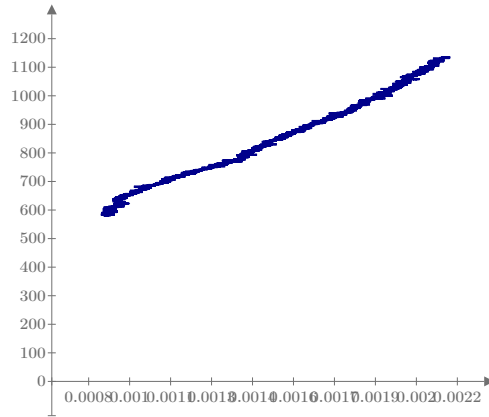


Fig H 4. Axial Load -depth for pile group 2P3S2B20

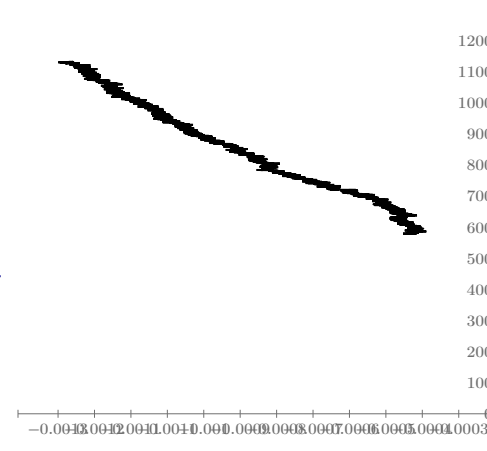
2.3.3 Bending Moment vs Time

$BM2G2P3S2B20 := ConvLd(G2P3S2B20HBM, 2, CFBM, 77, 3)$



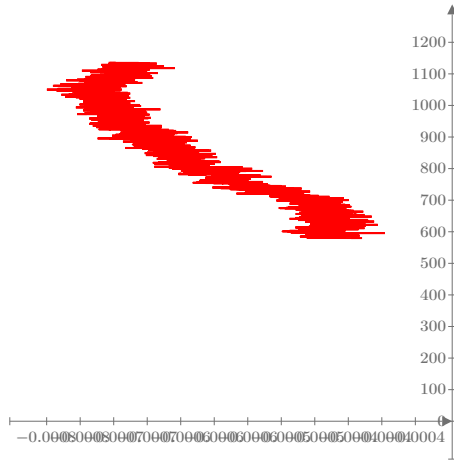
$G2P3S2B20HBM^{(5)}$

$$\frac{G2P3S2B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}{s}$$



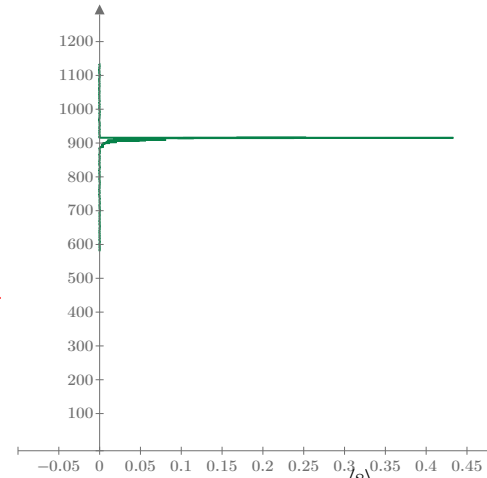
$G2P3S2B20HBM^{(6)}$

$$\frac{G2P3S2B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}{s}$$



$G2P3S2B20HBM^{(7)}$

$$\frac{G2P3S2B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}{s}$$



$G2P3S2B20HBM^{(8)}$

$$\frac{G2P3S2B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)}{s}$$

Fig H 5. Raw Data Bending Moment 2 for pile group 2P3S2B20

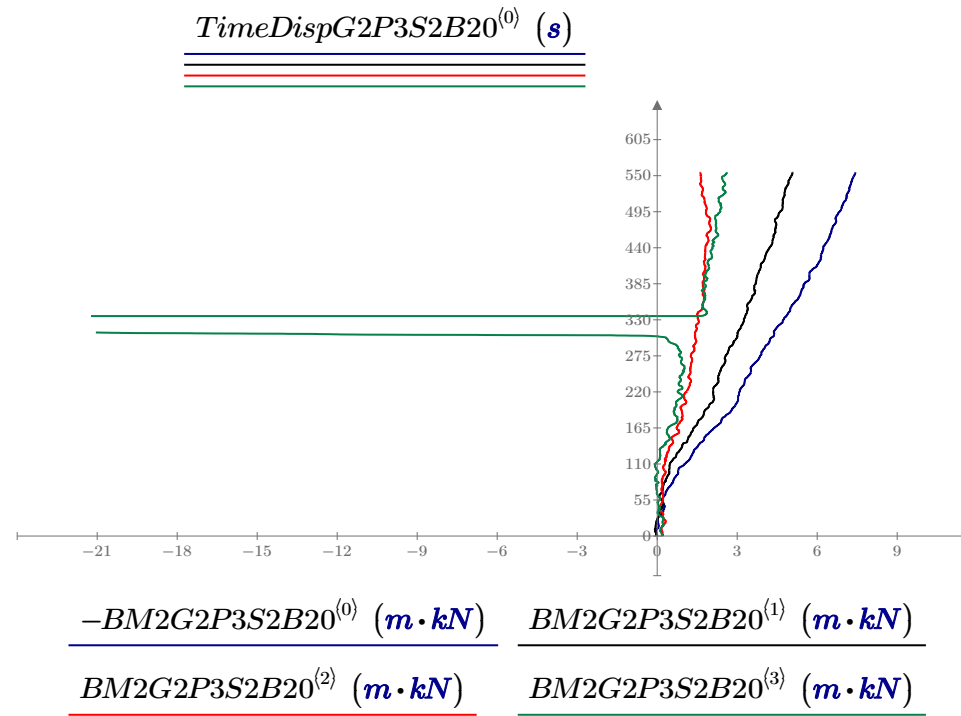


Fig H 6. Bending Moment 2 time history for pile group 2P3S2B20

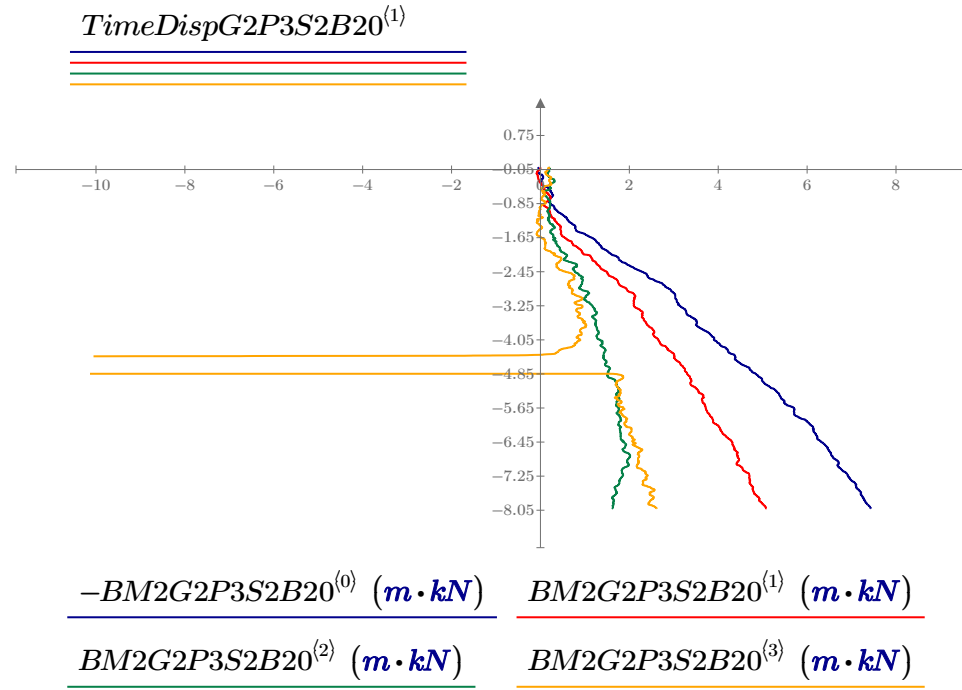


Fig H 7. Bending Moment 2 - displacement for pile group 2P3S2B20

$$BMM_{axdist2P3S2B20} := SGplotQP(BM2G2P3S2B20, TimeDispG2P3S2B20, 3) = \begin{bmatrix} -2.3931 & -4.9878 & -7.1004 & -7.4335 \\ 1.5098 & 3.3993 & 4.7797 & 5.073 \\ 1.5098 & 3.3993 & 4.7797 & 5.073 \\ 0.859 & 1.6825 & 1.6913 & 1.6294 \\ 0.859 & 1.6825 & 1.6913 & 1.6294 \\ 0.7155 & 1.7694 & 2.4172 & 2.6203 \end{bmatrix} m \cdot kN$$

Appendix H

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

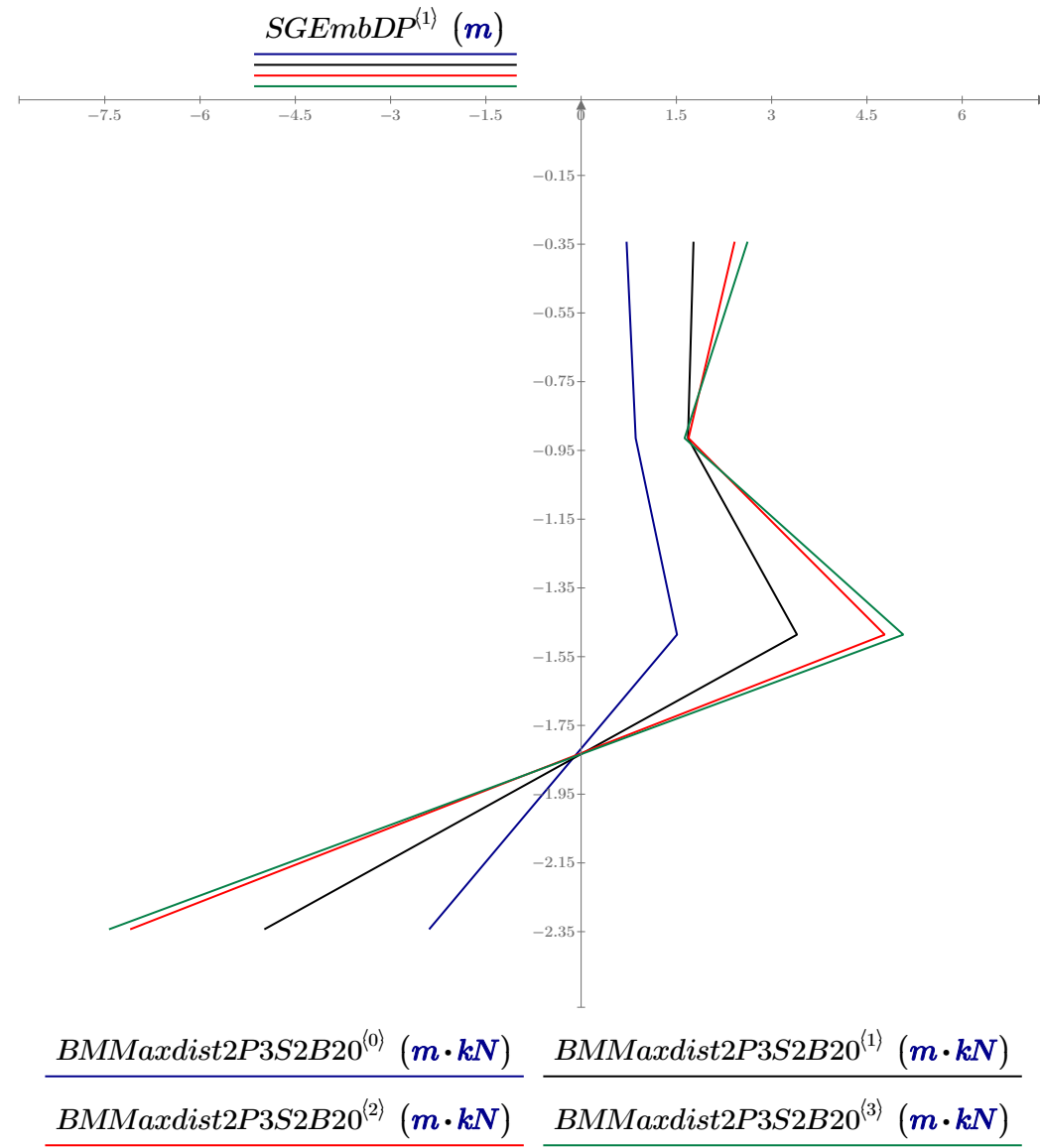


Fig H 8. Bending Moment 2 - depth for pile group 2P3S2B20

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) := || TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
                             || LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
                             || LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
                             || for i ∈ 0, 1..rows(LVDTRawData) - 1
                             ||   k_i ← (TimeLVDT_i - TimeLVDT_0)
                             ||   q_i ← -(LVDT1_i - LVDT1_0) · 2 · Nscalescifac0,0
                             ||   m_i ← -(LVDT2_i - LVDT2_0) · 2 · Nscalescifac0,0
                             ||   n_i ← -(TimeLVDT_i - TimeLVDT_0) · CmpRate · Nscalescifac0,0
                             || augment(k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-2P3B20D.xlsx"}, \text{"Sheet1 (2)!A2:C557"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDTC := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDTR := LVDT(LVDTRawData, 11)^{(2)}$

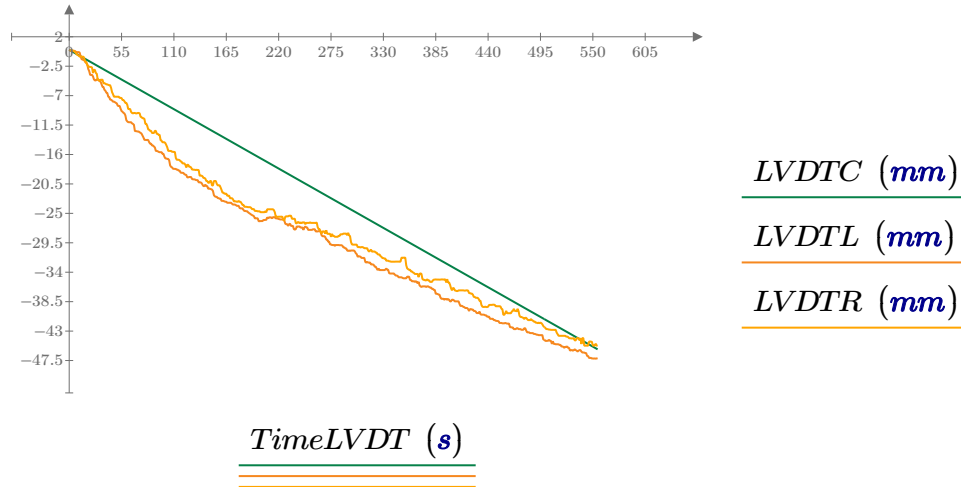


Fig H 9. LVDT displacements time history for pile group 2P3S2B20

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S2B20 Helix Pile Group

Function for determining the tilting of the plate

$$Tilt(SpacingDCDLR, SpacingDLDR) := \begin{cases} k \leftarrow (SpacingDCDLR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ q \leftarrow (SpacingDLDR) \cdot \text{mm} \cdot Nscale^{scale_{0,0}} \\ \text{for } i \in 0, 1 \dots \text{rows}(LVDTRawData) - 1 \\ \quad \left\| \begin{aligned} m_i &\leftarrow \frac{(LVDTC_i - LVDTR_i)}{k} \\ n_i &\leftarrow \frac{(LVDTC_i - LVDTL_i)}{k} \\ l_i &\leftarrow \frac{(LVDTR_i - LVDTL_i)}{q} \end{aligned} \right. \\ \text{augment}(m, n, l) \end{cases}$$

$$Rot4P3S2B0 := \text{augment} \left(\text{medsmooth} \left(Tilt(7.1, 7.8)^{(0)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(1)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(2)}, 99 \right) \right)$$

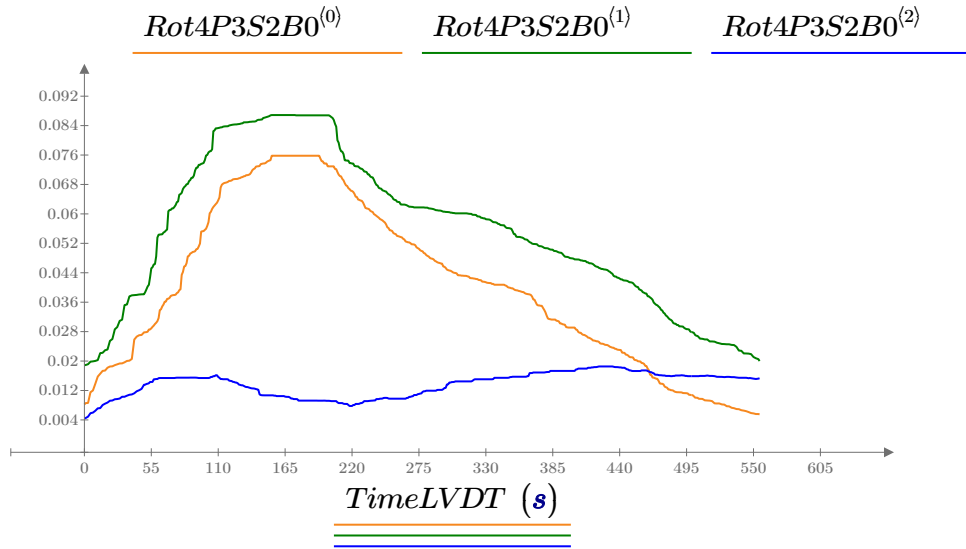


Fig H 10. LVDT rotations time history for pile group 2P3S2B20

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

1. Introduction

The series of sheets in Appendix I contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 4P3S2B10 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

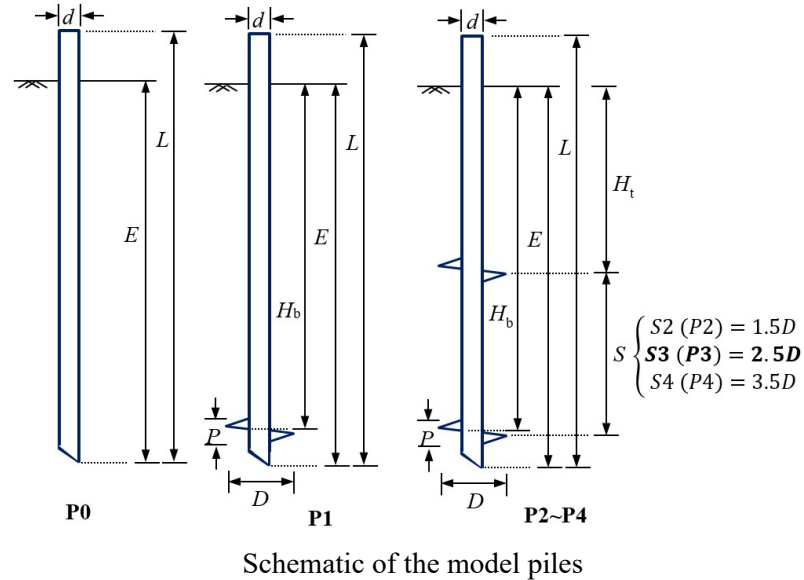
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CFAx1 := \begin{bmatrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ \quad \quad k_{i,j} \leftarrow CmbLdAx_{i,0} \\ \quad \quad q_{i,j} \leftarrow CalibdataPile_{i,j} \\ \quad \quad m_{i,j} \leftarrow \begin{cases} 0 & \text{if } q_{i,j} = 0 \\ \frac{k_{i,j}}{q_{i,j}} & \text{else} \end{cases} \end{bmatrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =	2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
	4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
	9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
	2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
	4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
	9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
	2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
	4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
	9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
	2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
	4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
	9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \frac{kN \cdot m}{V}$$

Calibration Factor: Here, the columns represents the Piles P0B1, P0B2, P3B1, P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \begin{aligned} & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \cdot \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \cdot \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & \text{SG1}_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG2}_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG3}_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & \text{SG4}_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(\text{SG1}^{(0)}, \text{smthn}), \text{medsmooth}(\text{SG2}^{(1)}, \text{smthn}), \text{medsmooth}(\text{SG3}^{(2)}, \text{smthn}), \text{medsmooth}(\text{SG4}^{(3)}, \text{smthn})) \end{aligned}
 \end{aligned}
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{aligned} & \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \cdot \mathbf{s} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{aligned}
 \end{aligned}$$

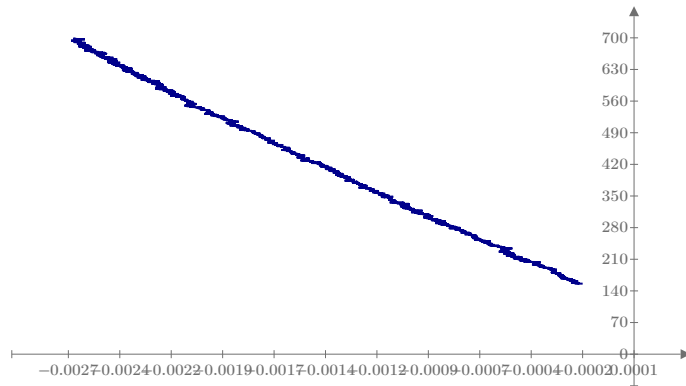
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$G4P3S2B10HBM := \text{READExcel}(\text{".\2P3B10G.xlsx"}, \text{"Sheet1 (2)!A3:M5423"})$

$\text{TimeDisp}G4P3S2B10 := \text{TimeZero}(G4P3S2B10HBM)$

$AxLdG4P3S2B10 := \text{ConvLd}(G4P3S2B10HBM, 3, CFAxl, 11, 1)$



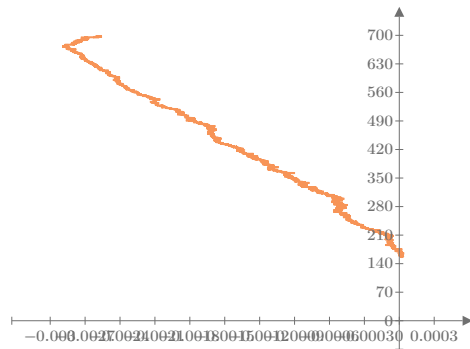
$G4P3S2B10H$



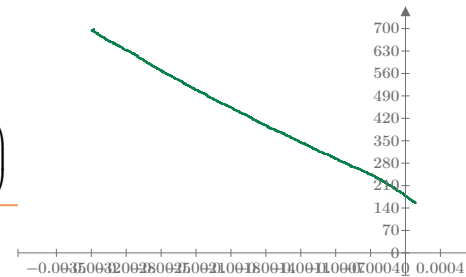
$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

$G4P3S2B10HBM^{(9)}$

$G4P3S2B10HBM^{(10)}$



$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G4P3S2B10HBM^{(12)}$

$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

$G4P3S2B10HBM^{(11)}$

Fig I 1. Rawdata axial load time history for pile group 3P3B10G

Appendix I
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

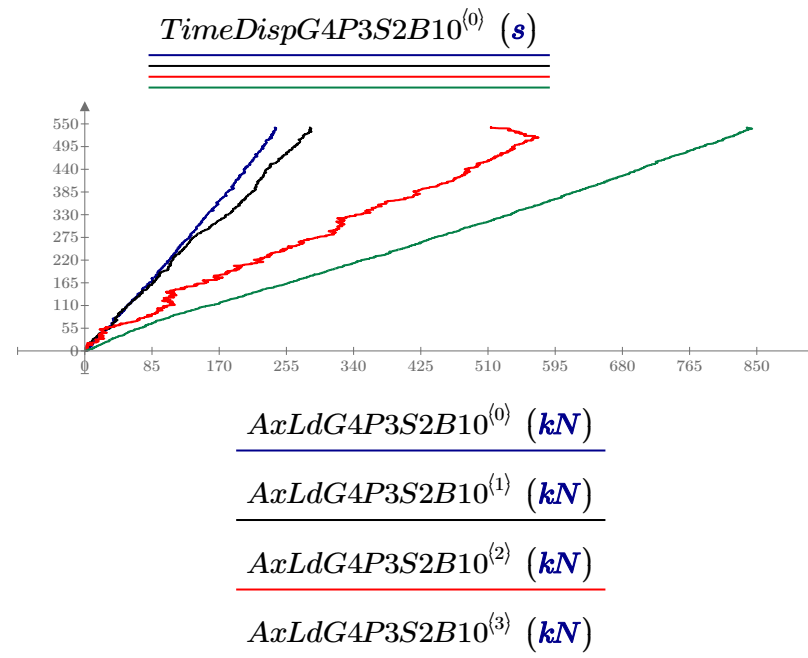


Fig I 2. Axial Load time history for pile group 3P3B10G

Appendix I

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

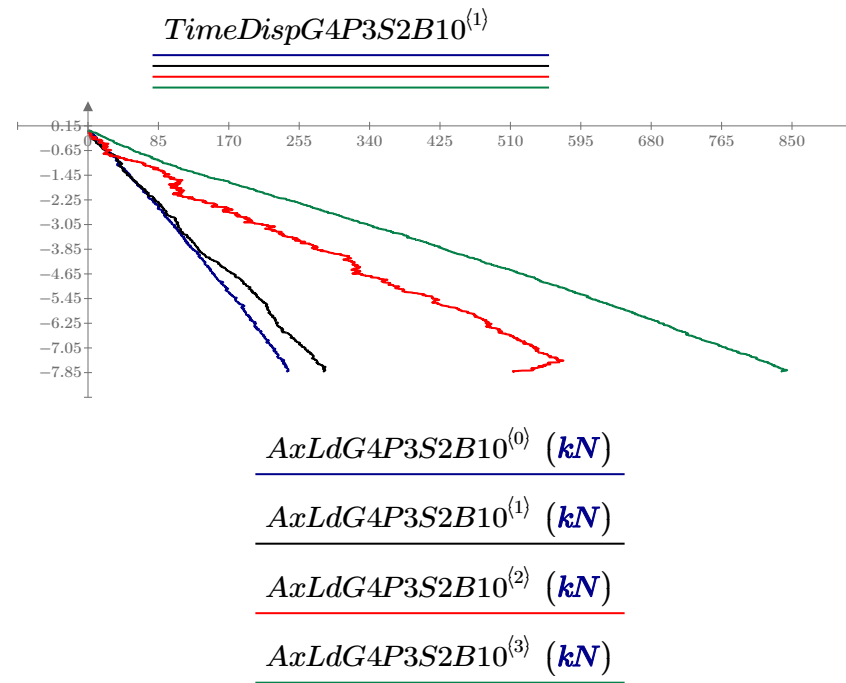


Fig I 3. Axial Load -displacement for pile group 3P3B10G

Appendix I

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```
SGplotQP (AxLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
  | augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  | else
  | augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  QP1 ← if PileNum = 0
  | augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  | else
  | augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near"))
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near"))
  combined ← if PileNum = 0
  | stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  | else
  | stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  combined
```

$$Qdist4P3S2B10 := SGplotQP (AxLdG4P3S2B10 , TimeDispG4P3S2B10 , 3) = \begin{bmatrix} 85.578 & 163.5176 & 235.7991 & 242.023 \\ 90.665 & 190.3965 & 276.7949 & 283.817 \\ 90.665 & 190.3965 & 276.7949 & 283.817 \\ 166.4972 & 362.5433 & 569.6703 & 514.6922 \\ 166.4972 & 362.5433 & 569.6703 & 514.6922 \\ 271.3103 & 560.9322 & 817.2943 & 837.1007 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{sclfac_{0,0}} \quad \begin{array}{l} SG \text{ embedment depth in prototype scale. Here, colm 0-4 represents} \\ P0 \text{ to P4. Row 0 to 5 represents depth to strain SG 1 to 4} \end{array}$$

Appendix I

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

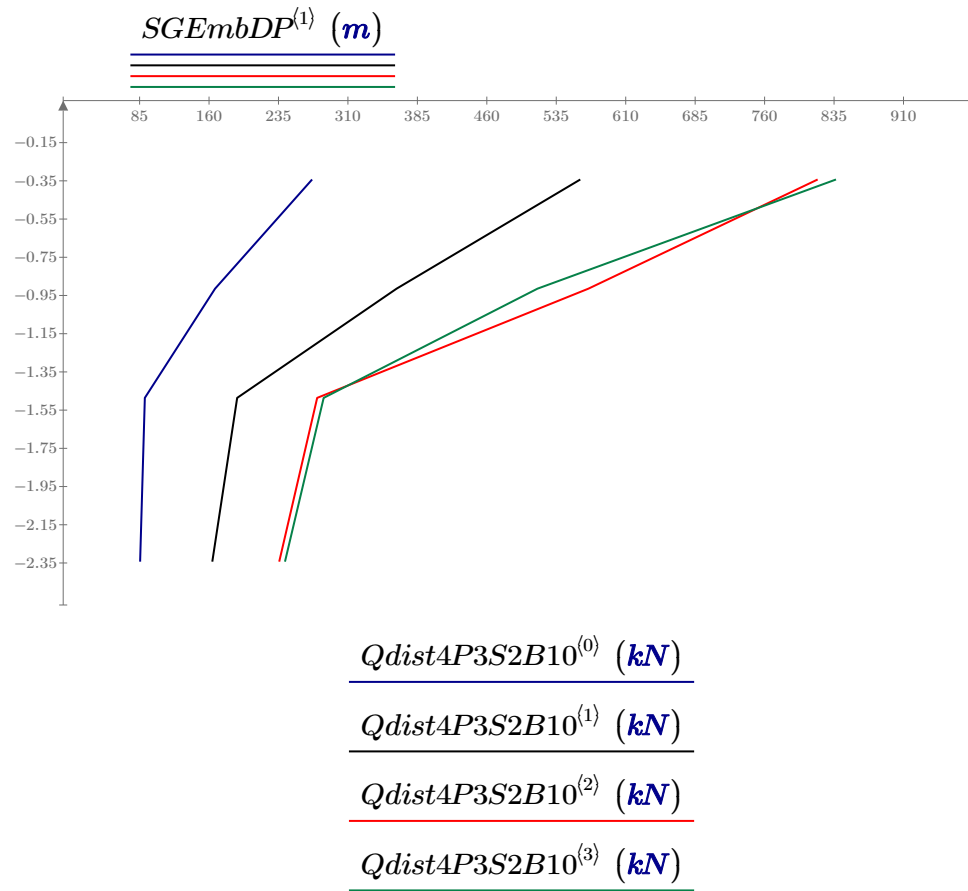


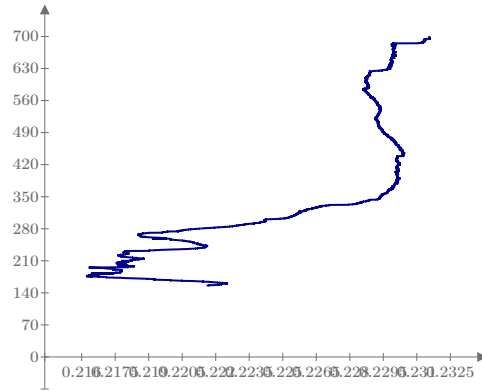
Fig I 4. Axial Load -depth for pile group 3P3B10G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

2.3.3 Bending Moment vs Time

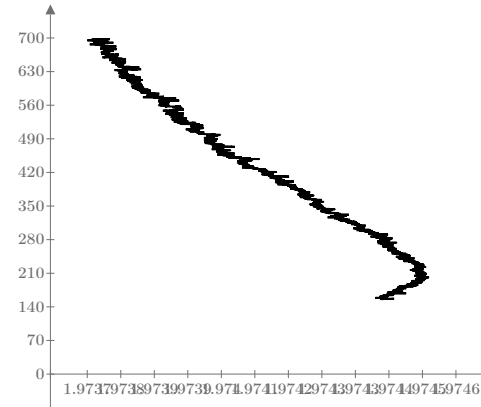
$BM1G4P3S2B10 := ConvLd(G4P3S2B10HBM, 3, CFBM, 111, 2)$

$BM2G4P3S2B10 := ConvLd(G4P3S2B10HBM, 5, CFBM, 77, 3)$



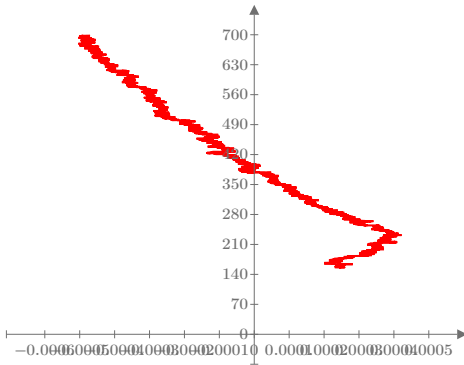
$G4P3S2B10HBM^{(1)}$

$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



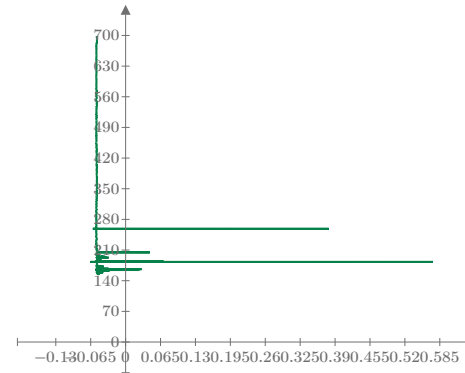
$G4P3S2B10HBM^{(2)}$

$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G4P3S2B10HBM^{(3)}$

$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

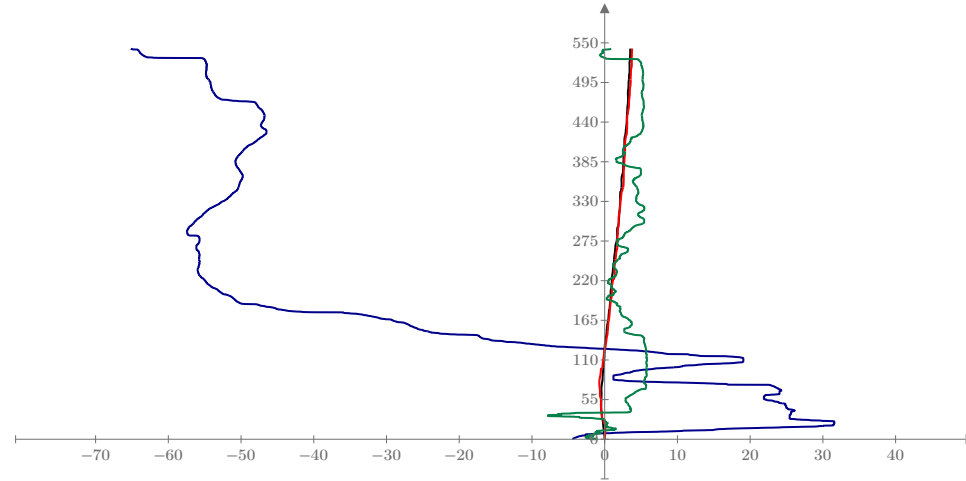


$G4P3S2B10HBM^{(4)}$

$G4P3S2B10HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

Fig I 5. Raw Data Bending Moment 1 for pile group 3P3B10G

$TimeZero(G4P3S2B10HBM)^{(0)} (s)$



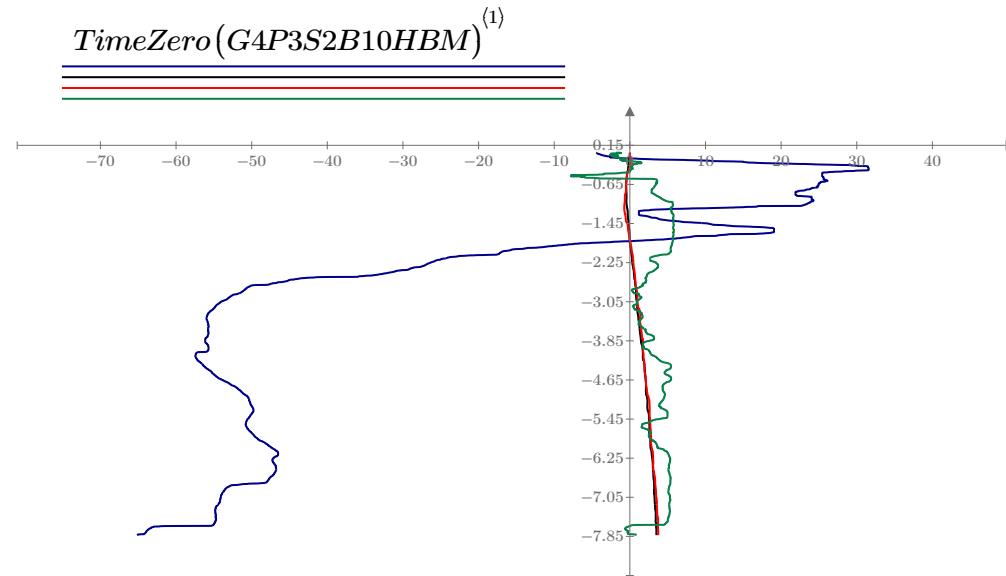
$BM1G4P3S2B10^{(0)} (m \cdot kN)$

$BM1G4P3S2B10^{(1)} (m \cdot kN)$

$BM1G4P3S2B10^{(2)} (m \cdot kN)$

$BM1G4P3S2B10^{(3)} (m \cdot kN)$

Fig I 6. Bending Moment 1 time history for pile group 3P3B10G



$BM1G4P3S2B10^{(0)} (m \cdot kN)$	$BM1G4P3S2B10^{(1)} (m \cdot kN)$
$BM1G4P3S2B10^{(2)} (m \cdot kN)$	$BM1G4P3S2B10^{(3)} (m \cdot kN)$

Fig I 7. Bending Moment 1 - displacement for pile group 3P3B10G

$$BMM_{axdist4P3S2B10} := SGplotQP(BM1G4P3S2B10, TimeDispG4P3S2B10, 3) = \begin{bmatrix} -33.5012 & -50.511 & -54.7045 & -65.1459 \\ 0.5547 & 2.2723 & 3.4277 & 3.5251 \\ 0.5547 & 2.2723 & 3.4277 & 3.5251 \\ 0.6671 & 2.4511 & 3.731 & 3.762 \\ 0.6671 & 2.4511 & 3.731 & 3.762 \\ 2.2961 & 4.5271 & 5.0157 & 0.8834 \end{bmatrix} m \cdot kN$$

Appendix I
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

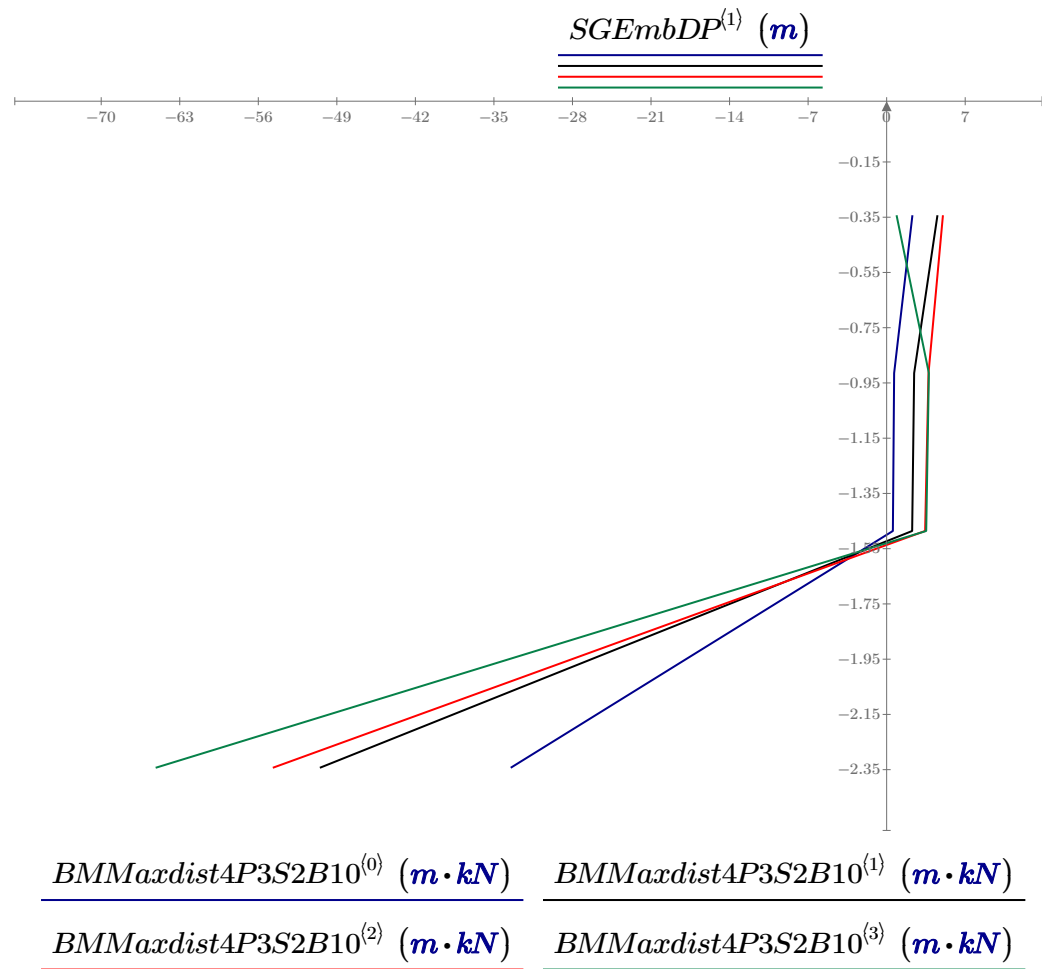


Fig I 8. Bending Moment 1 - depth for pile group 3P3B10G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

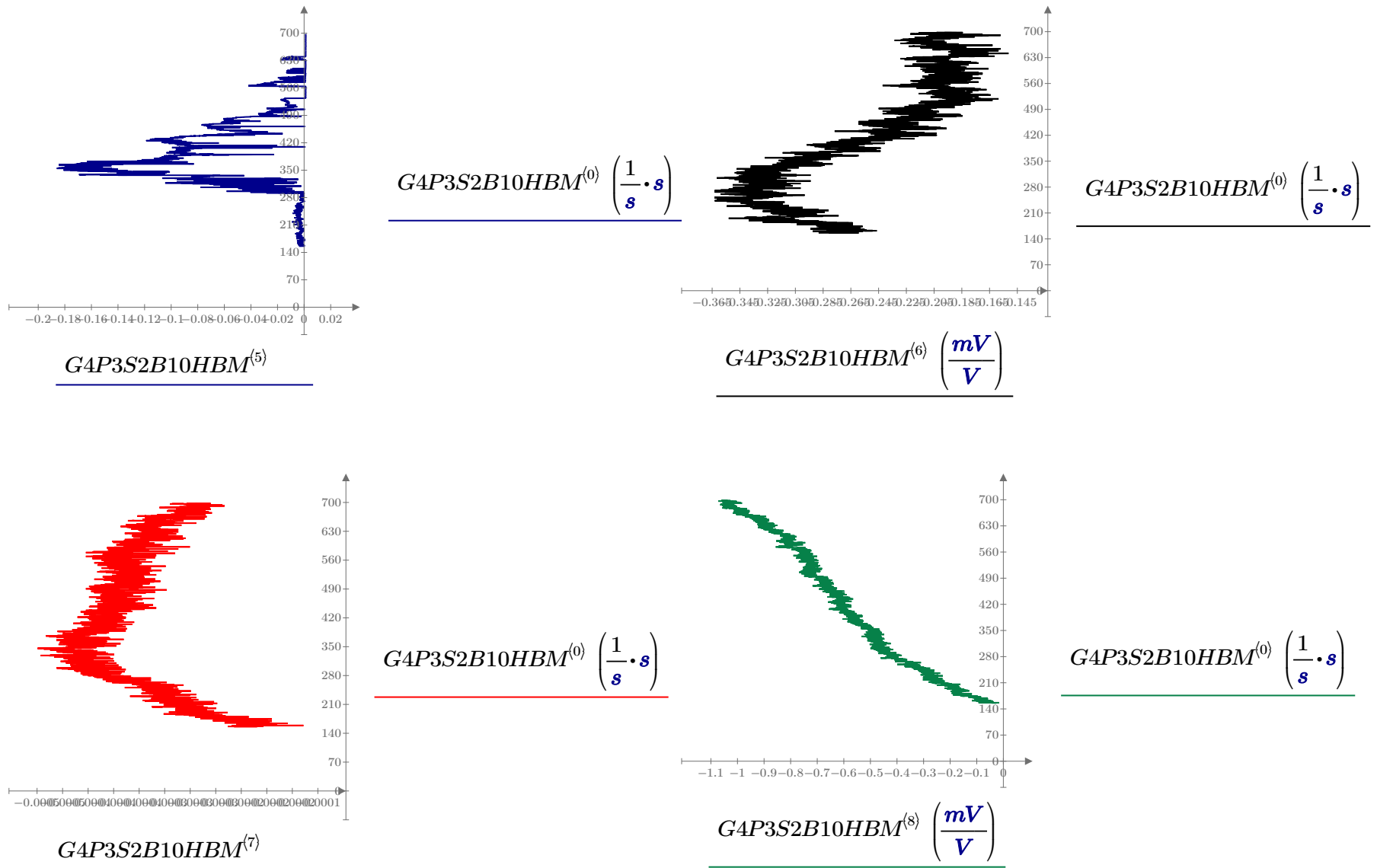


Fig I 9. Raw Data Bending Moment 2 for pile group 3P3B10G

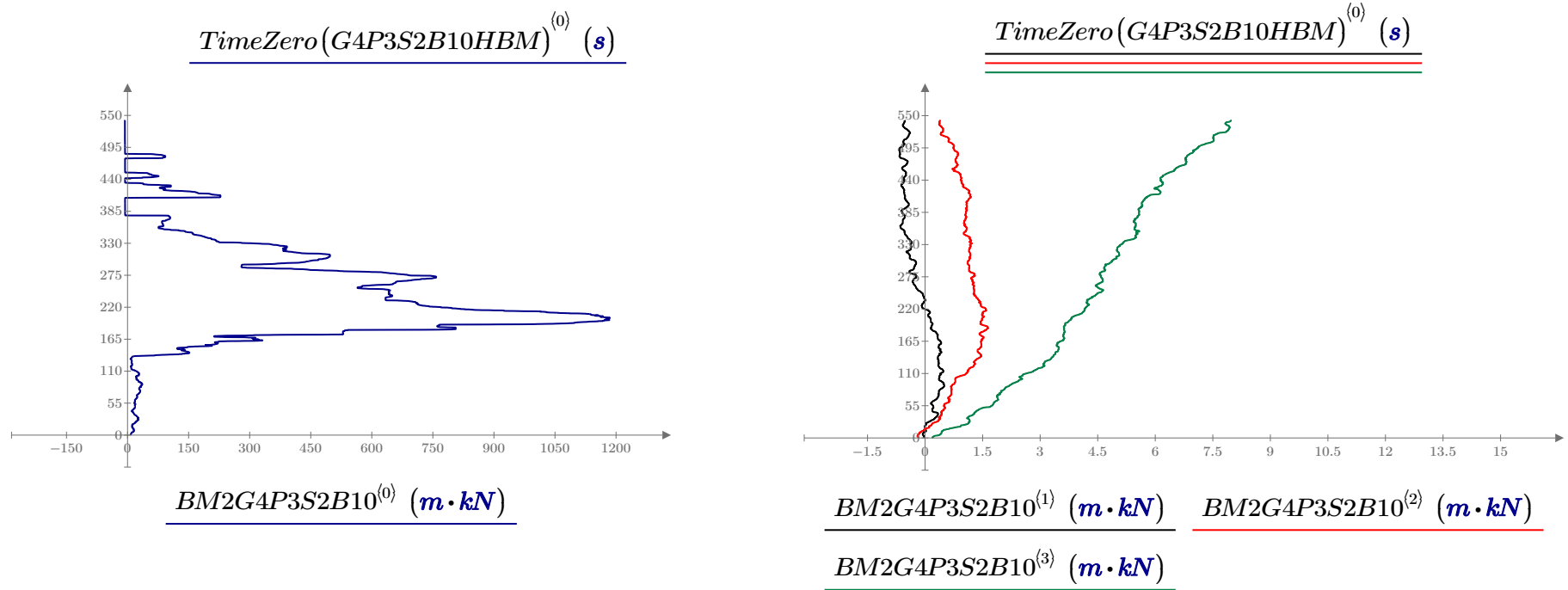


Fig I 10. Bending Moment 2 time history for pile group 3P3B10G

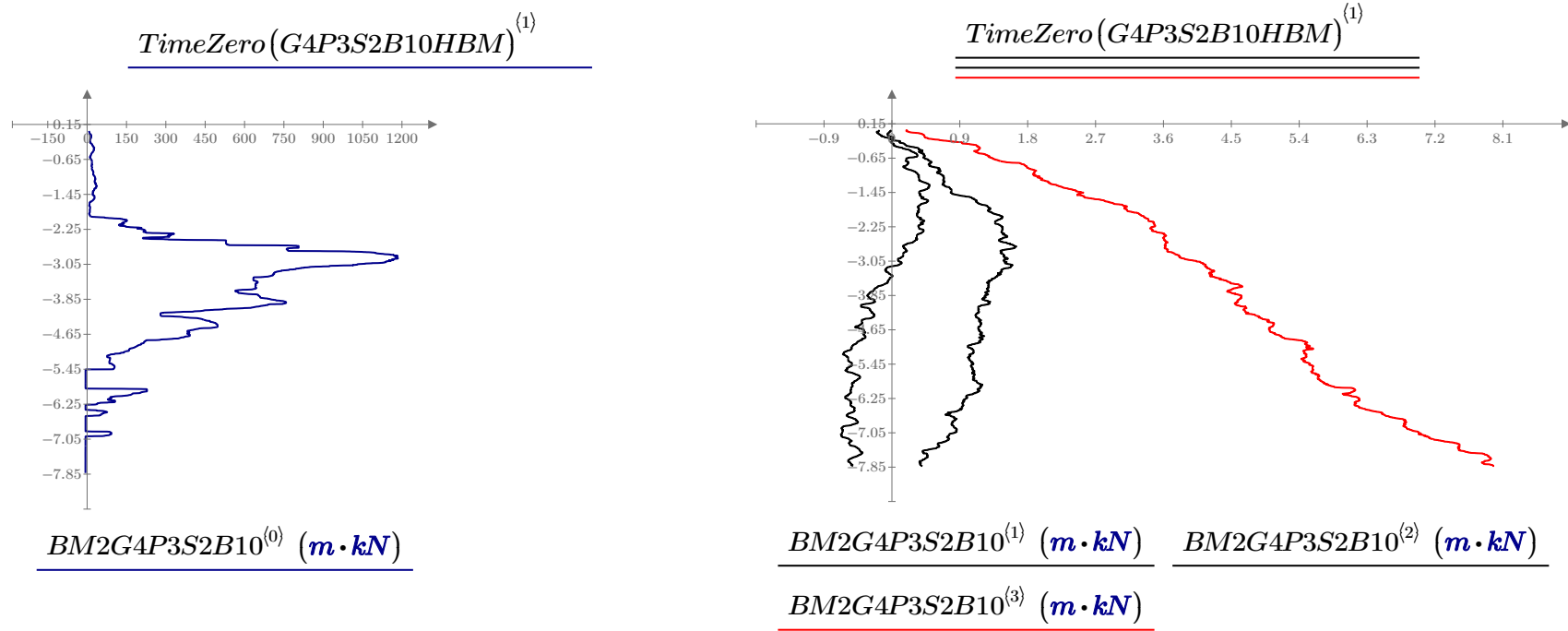


Fig I 11. Bending Moment 2 - displacement for pile group 3P3B10G

$$BMMindist4P3S2B10 := SGplotQP(BM2G4P3S2B10, TimeDispG4P3S2B10, 3) = \begin{bmatrix} 526.6036 & 160.3146 & -6.4435 & -6.4633 \\ 0.3301 & -0.5101 & -0.3901 & -0.5401 \\ 0.3301 & -0.5101 & -0.3901 & -0.5401 \\ 1.489 & 1.0535 & 0.4052 & 0.4052 \\ 1.489 & 1.0535 & 0.4052 & 0.4052 \\ 3.6043 & 5.4971 & 7.6279 & 7.968 \end{bmatrix} m \cdot kN$$

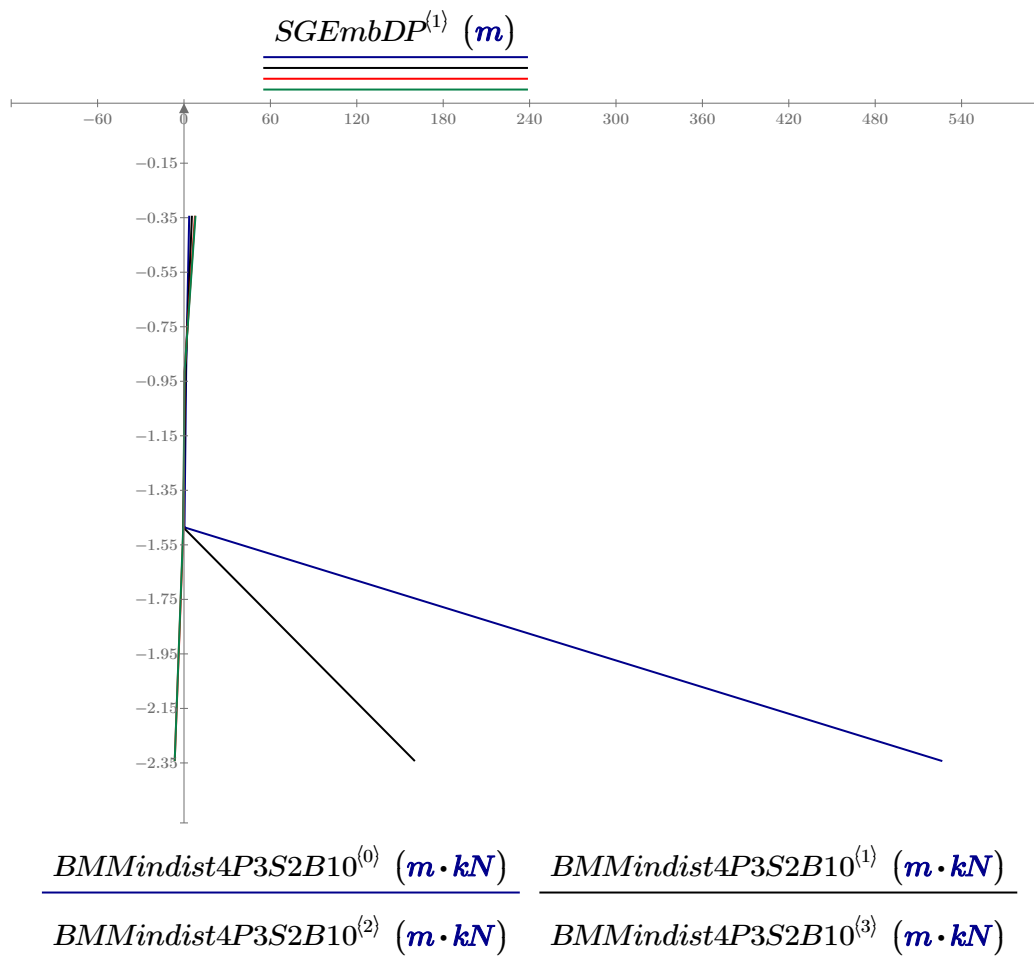


Fig I 12. Bending Moment 2 - depth for pile group 3P3B10G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT (LVDTRawData, smthn) := || TimeLVDT ← submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 0, 0) s
    LVDT1 ← medsmooth (submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 1, 1) mm, smthn)
    LVDT2 ← medsmooth (submatrix (LVDTRawData, 0, rows (LVDTRawData) - 1, 2, 2) mm, smthn)
    for i ∈ 0, 1..rows (LVDTRawData) - 1
        || k_i ← (TimeLVDT_i - TimeLVDT_0)
        || q_i ← -(LVDT1_i - LVDT1_0) · 2 · Nscalescfac0,0
        || m_i ← -(LVDT2_i - LVDT2_0) · 2 · Nscalescfac0,0
        || n_i ← -(TimeLVDT_i - TimeLVDT_0) · CmpRate · Nscalescfac0,0
    || augment (k, q, m, n)

```

$LVDTRawData := \text{READExcel}(\text{".\Nav-2P3B10G.xlsx"}, \text{"Sheet1 (2)!A2:C537"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDT1 := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDT2 := LVDT(LVDTRawData, 11)^{(2)}$

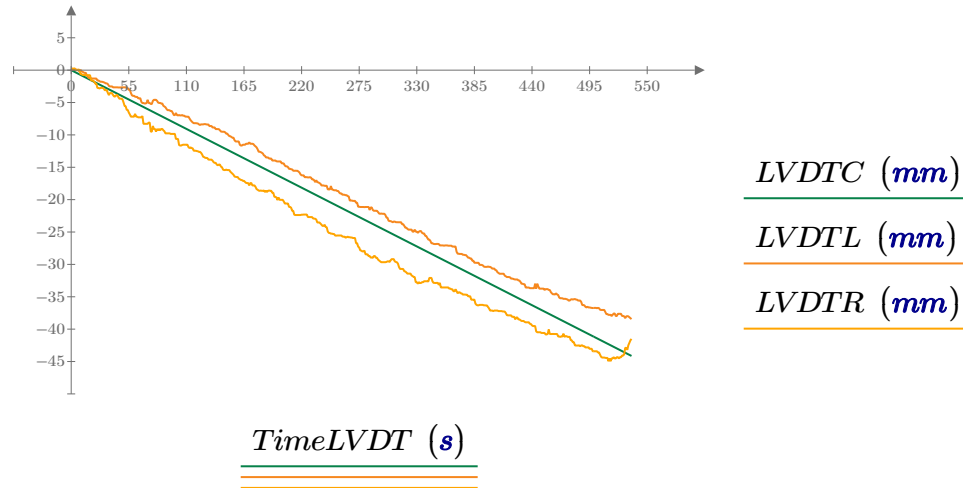


Fig I 13. LVDT displacements time history for pile group 3P3B10G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 4P3S2B10 Helix Pile Group

Function for determining the tilting of the plate

$$\begin{aligned}
 \text{Tilt}(\text{SpacingDCDLR}, \text{SpacingDLDR}) := & \begin{array}{l} k \leftarrow (\text{SpacingDCDLR}) \cdot \text{mm} \cdot \text{Nscale}_{0,0}^{sclfac} \\ q \leftarrow (\text{SpacingDLDR}) \cdot \text{mm} \cdot \text{Nscale}_{0,0}^{sclfac} \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{LVDTRawData}) - 1 \\ \quad \begin{array}{l} m_i \leftarrow \frac{(\text{LVDTC}_i - \text{LVDTR}_i)}{k} \\ n_i \leftarrow \frac{(\text{LVDTC}_i - \text{LVDTL}_i)}{k} \\ l_i \leftarrow \frac{(\text{LVDTR}_i - \text{LVDTL}_i)}{q} \end{array} \\ \text{augment}(m, n, l) \end{array}
 \end{aligned}$$

$$\text{Rot4P3S2B0} := \text{augment}\left(\text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(0)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(1)}, 99\right), \text{medsmooth}\left(\text{Tilt}(7.1, 7.8)^{(2)}, 99\right)\right)$$

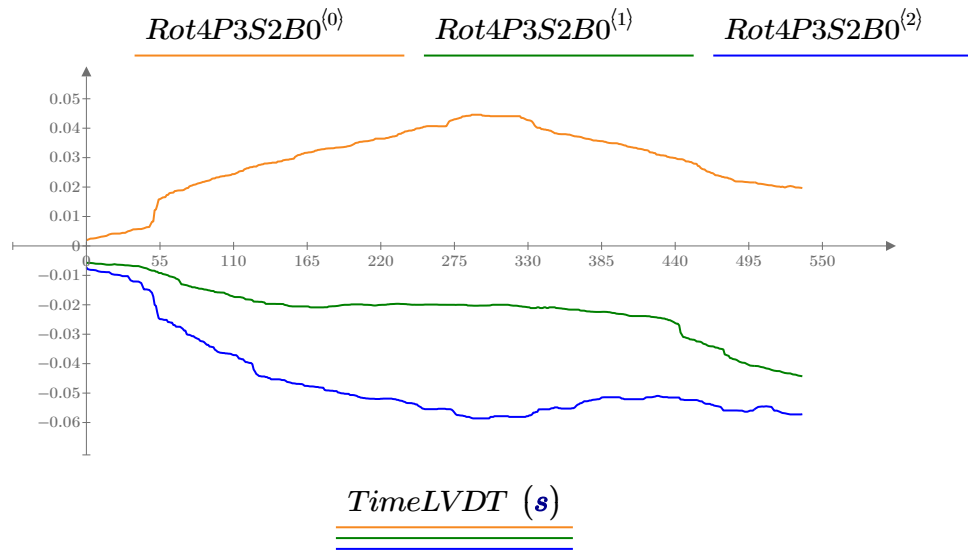


Fig I 14. LVDT rotations time history for pile group 3P3B10G

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

1. Introduction

The series of sheets in Appendix J contains the data conversion and processing procedures specifically for the NI03 centrifuge test series on 2P3S3B20 Helix Pile Group. For the data conversion procedures, the raw data files were first corrected by subtracting the initial value of pre spin data depending on file index. The data were then converted into engineering units through recalibrations of the strain gauges in the centrifuge data logger.

2. HBM Data Conversion

HBM data were recorded by the HBM Data Logger connected to the main computer unit of the GeoCerf centrifuge.

2.1 General Information

2.1.1 Model Pile Dimensions

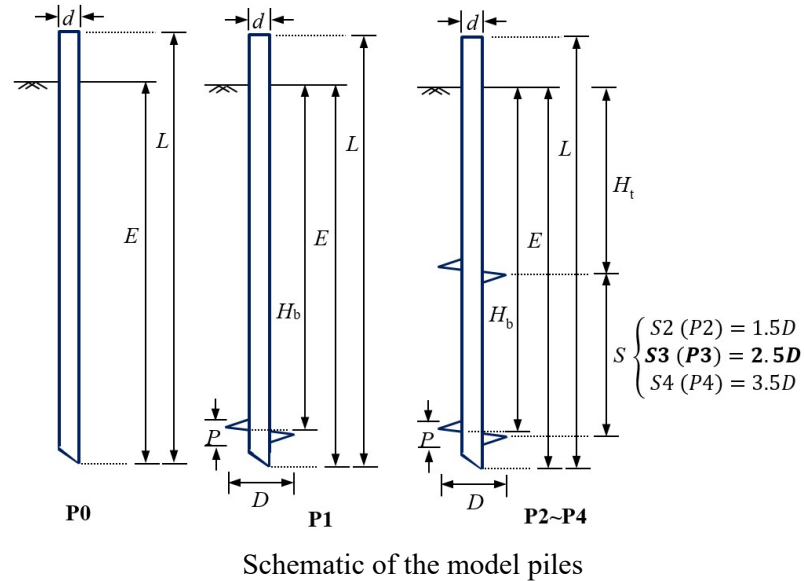
$L := 271.8 \text{ mm}$	Length of the Pile
$d := 12.7 \text{ mm}$	Diameter of the shaft
$D := 38.1 \text{ mm}$	Diameter of the helix
$E := 169.1 \text{ mm}$	Embedment depth of pile
$H_b := 150 \text{ mm}$	Depth to bottom helix
$H_t := [150] \text{ mm}$	Depth to top helix
$P_s := \pi \cdot D = 0.1197 \text{ m}$	Perimeter of the Helical Pile Shaft
$H_{eff} := (H_b - D)$	Effective Shaft Length
$P := 12.7 \text{ mm}$	Pitch of the helix

2.1.2 Properties of Sand

$\gamma := 16.1 \frac{kN}{m^3}$	Unit Weight
$\varphi := 31.2 \text{ deg}$	CV Friction Angle
$\delta := \left(\frac{3}{4} \cdot \varphi \right) = 23.4 \text{ deg}$	CV Dilation Angle

2.1.3 Centrifuge Scale

$NoSGages := 4$	1 refers to the Strain Gage at the bottom and 4 the Strain Gage at the top of the pile; Total No of Strain Gages: P0=2, P1=3, P2 to P4= 4
$Nscale := 15$	Centrifuge g-level
$sclfac := [1 \ 2 \ 3]$	Centrifuge scale factor N^{scale} , 1 for displacement , 2 for force, 3 for Moment



Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

2.1.5 Loading Conditions

$$CmpRate := 0.33 \frac{mm}{min} = 0.0055 \frac{mm}{s} \quad \text{Actuator Loading rate in compression}$$

2.2 Calibration of the Strain Gages in HBM Data Logger

2.2.1 Calibration of Axial Strain Gages

RawDataCalib := READEXCEL (“..\Finalized NI01\Calibration SGages HBM Centrifuge Corrected.xlsx”, “Sheet1!A1:G12”)

$$RawDataCalib = \begin{bmatrix} 4.427 & 1 & 0.076 & 0.104 & 0.149 & 0.098 & 0.132 \\ 7.97 & 1 & 0.152 & 0.171 & 0.23 & 0.195 & 0.244 \\ 13.606 & 1 & 0.391 & 0.295 & 0.343 & 0.287 & 0.336 \\ 4.427 & 2 & 0.048 & 0.06 & 0.078 & 0.091 & 0.1 \\ 7.97 & 2 & 0.053 & 0.114 & 0.114 & 0.136 & 0.194 \\ 13.606 & 2 & 0.088 & 0.214 & 0.161 & 0.225 & 0.231 \\ 4.427 & 3 & 0 & 0.043 & 0.028 & 0.052 & 0.037 \\ 7.97 & 3 & 0 & 0.063 & 0.151 & 0.087 & 0.078 \\ 13.606 & 3 & 0 & 0.127 & 0.199 & 0.149 & 0.112 \\ 4.427 & 4 & 0 & 0 & 0.089 & 0.035 & 0.028 \\ 7.97 & 4 & 0 & 0 & 0.109 & 0.067 & 0.055 \\ 13.606 & 4 & 0 & 0 & 0.145 & 0.127 & 0.141 \end{bmatrix}$$

Colm 0 represents calibration loads in kg, Colm 1 represents Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0,P1,P2,P3 and P4 respectively

$$CmbLdAx := RawDataCalib^{(0)} \text{ kg} \cdot g \quad \text{Load Combinations}$$

$$CalibdataPile := \text{submatrix}(RawDataCalib, 0, \text{rows}(RawDataCalib) - 1, 2, 6) \cdot 10^{-3} \cdot \frac{mV}{V} \quad \text{HBM Strain Gage Data}$$

Function for Calibration factor for all strain gages in each pile

$$CF_{Axl} := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows}(CalibdataPile) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(CalibdataPile) - 1 \\ \quad \quad k_{i,j} \leftarrow CmbLdAx_{i,0} \\ \quad \quad q_{i,j} \leftarrow CalibdataPile_{i,j} \\ \quad \quad m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad \quad \quad 0 \\ \quad \quad \quad \text{else} \\ \quad \quad \quad \frac{k_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 571.237 & 417.443 & 291.369 & 443 & 328.894 \\ 514.204 & 457.07 & 339.822 & 400.815 & 320.324 \\ 341.251 & 452.303 & 389.007 & 464.91 & 397.111 \\ 904.459 & 723.567 & 556.59 & 477.077 & 434.14 \\ 1474.698 & 685.605 & 685.605 & 574.699 & 402.881 \\ 1516.242 & 623.501 & 828.753 & 593.019 & 577.616 \\ 0 & 1009.629 & 1550.501 & 834.885 & 1173.352 \\ 0 & 1240.619 & 517.609 & 898.379 & 1002.038 \\ 0 & 1050.624 & 670.499 & 895.499 & 1191.333 \\ 0 & 0 & 487.798 & 1240.401 & 1550.501 \\ 0 & 0 & 717.055 & 1166.552 & 1421.073 \\ 0 & 0 & 920.202 & 1050.624 & 946.307 \end{bmatrix} \frac{kN}{mV} \cdot \frac{mV}{V}$$

Calibration Factor. Here, the columns represents the Piles from P0 to P4 (left to right) and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three load combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

2.2.1 Calibration of Bending Strain Gages

RawDataCalibBend := READEXCEL (“.\CalibBendingRawData.xlsx”, “Sheet2!A2:I13”)

RawDataCalibBend =

2.404	212	1	0.003	0.0031	0.0027	0.0023	0.0025	0.0024
4.411	212	1	0.0057	0.0048	0.0045	0.0049	0.0055	0.0044
9.357	212	1	0.0129	0.0124	0.0126	0.011	0.016	0.0104
2.404	147	2	0	0	0.0019	0.0022	0.0019	0.0016
4.411	147	2	0	0	0.0033	0.0041	0.0039	0.003
9.357	147	2	0	0	0.0085	0.0089	0.009	0.0069
2.404	120	3	0	0	0.0015	0.0017	0.0016	0.0014
4.411	120	3	0	0	0.0026	0.0033	0.0035	0.0024
9.357	120	3	0	0	0.0068	0.0071	0.0075	0.0054
2.404	85	4	0.0009	0.0011	0.0009	0.0012	0.0012	0.0009
4.411	85	4	0.0021	0.002	0.0017	0.0022	0.0021	0.0016
9.357	85	4	0.0041	0.0047	0.0046	0.0047	0.0043	0.0032

Colm 0 represents calibration loads in kg, Colm 1 represents the moment arm, Colm 2 represents the Strain Gage Number, Colm 2-6 represents Strain Gage HBM readings for piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively

CmbLoadMoment := RawDataCalibBend⁽⁰⁾ **kg • g**

Load Combinations

CmbMArm := RawDataCalibBend⁽¹⁾ **mm**

Moment Arm Combinations

CalibdataPileM := submatrix (RawDataCalibBend, 0, rows (RawDataCalibBend) – 1, 3, 8) • $\frac{mV}{V}$ **HBM Strain Gage Data**

Function for Calibration factor for all strain gages in each pile

$$CFBM := \begin{matrix} \text{for } i \in 0, 1 \dots \text{rows} (CalibdataPileM) - 1 \\ \text{for } j \in 0, 1 \dots \text{cols} (CalibdataPileM) - 1 \\ k_{i,j} \leftarrow CmbLoadMoment_{i,0} \\ l_{i,j} \leftarrow CmbMArm_{i,0} \\ q_{i,j} \leftarrow CalibdataPileM_{i,j} \\ m_{i,j} \leftarrow \text{if } q_{i,j} = 0 \\ \quad 0 \\ \text{else} \\ \quad \frac{k_{i,j} \cdot l_{i,j}}{q_{i,j}} \end{matrix} = \begin{bmatrix} 1.672 & 1.617 & 1.844 & 2.164 & 2.04 & 2.127 \\ 1.603 & 1.911 & 2.02 & 1.887 & 1.661 & 2.108 \\ 1.505 & 1.573 & 1.543 & 1.762 & 1.214 & 1.88 \\ 0 & 0 & 1.796 & 1.568 & 1.863 & 2.113 \\ 0 & 0 & 1.945 & 1.54 & 1.643 & 2.099 \\ 0 & 0 & 1.581 & 1.519 & 1.5 & 1.958 \\ 0 & 0 & 1.849 & 1.645 & 1.736 & 2.08 \\ 0 & 0 & 1.989 & 1.578 & 1.475 & 2.136 \\ 0 & 0 & 1.624 & 1.562 & 1.464 & 2.032 \\ 2.33 & 1.805 & 2.132 & 1.656 & 1.698 & 2.227 \\ 1.794 & 1.802 & 2.125 & 1.71 & 1.751 & 2.327 \\ 1.889 & 1.67 & 1.707 & 1.656 & 1.814 & 2.437 \end{bmatrix} \frac{kN \cdot m}{V}$$

Calibration Factor. Here, the columns represents the Piles P0B1, P0B2, P3B1,P3B2, P3B3 and P3B4 respectively and the rows represents the Strain Gage readings SG1 to SG4 (top to bottom) for three moment combinations

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

2.3.2 Axial Load vs Time

Function for determining the Time, Displacement and Axial Load Distribution in each pile

$$\begin{aligned}
 \text{ConvLd}(\text{RawdataHBM}, \text{PileNum}, \text{CF}, \text{smthn}, \text{LdType}) := & \text{RawDataSG} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 9, 12) \cdot \frac{mV}{V} \\ & \text{else if } \text{LdType} = 2 \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 1, 4) \cdot \frac{mV}{V} \\ & \text{else} \\ & -\text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 5, 8) \cdot \frac{mV}{V} \end{aligned} \right\| \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{RawDataSG}) - 1 \\ \quad \text{for } j \in 0, 1 \dots \text{cols}(\text{RawDataSG}) - 1 \\ \quad \quad \left\| \begin{aligned} & q_{i,j} \leftarrow \text{RawDataSG}_{i,j} - \text{RawDataSG}_{0,j} \\ & SG1_{i,0} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,0} \cdot \text{mean}(\text{submatrix}(\text{CF}, 0, 2, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & SG2_{i,1} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,1} \cdot \text{mean}(\text{submatrix}(\text{CF}, 3, 5, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & SG3_{i,2} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,2} \cdot \text{mean}(\text{submatrix}(\text{CF}, 6, 8, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \\ & SG4_{i,3} \leftarrow \begin{cases} \text{if } \text{LdType} = 1 \\ \left\| \begin{aligned} & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,1}} \right) \\ & \text{else} \\ & \left(q_{i,3} \cdot \text{mean}(\text{submatrix}(\text{CF}, 9, 11, \text{PileNum}, \text{PileNum})) \cdot \text{Nscale}^{\text{sclfac}_{0,2}} \right) \end{aligned} \right\| \end{cases} \end{aligned} \right\| \\ \text{augment}(\text{medsmooth}(SG1^{(0)}, \text{smthn}), \text{medsmooth}(SG2^{(1)}, \text{smthn}), \text{medsmooth}(SG3^{(2)}, \text{smthn}), \text{medsmooth}(SG4^{(3)}, \text{smthn}))
 \end{aligned}$$

Function for determining the time and displacement

$$\begin{aligned}
 \text{TimeZero}(\text{RawdataHBM}) := & \begin{cases} \text{TimeP} \leftarrow \text{submatrix}(\text{RawdataHBM}, 0, \text{rows}(\text{RawdataHBM}) - 1, 0, 0) \\ \text{for } i \in 0, 1 \dots \text{rows}(\text{TimeP}) - 1 \\ \quad \left\| \begin{aligned} & k_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \\ & q_i \leftarrow (\text{TimeP}_i - \text{TimeP}_0) \cdot \frac{\text{CmpRate}}{D} \cdot 100 \end{aligned} \right\| \\ \text{augment}(k, q) \end{cases}
 \end{aligned}$$

Appendix J

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

There were four strain gages placed within the P3 pile. The following sub sections provides the details on the load distributions:

$G2P3S3B20HBM := \text{READExcel}(\text{".\3P3B20D.xlsx"}, \text{"Sheet1 (2)!A3:M8883"})$

$\text{TimeDisp}G2P3S3B20 := \text{TimeZero}(G2P3S3B20HBM)$

$\text{AxLd}G2P3S3B20 := \text{ConvLd}(G2P3S3B20HBM, 3, \text{CFAxl}, 11, 1)$

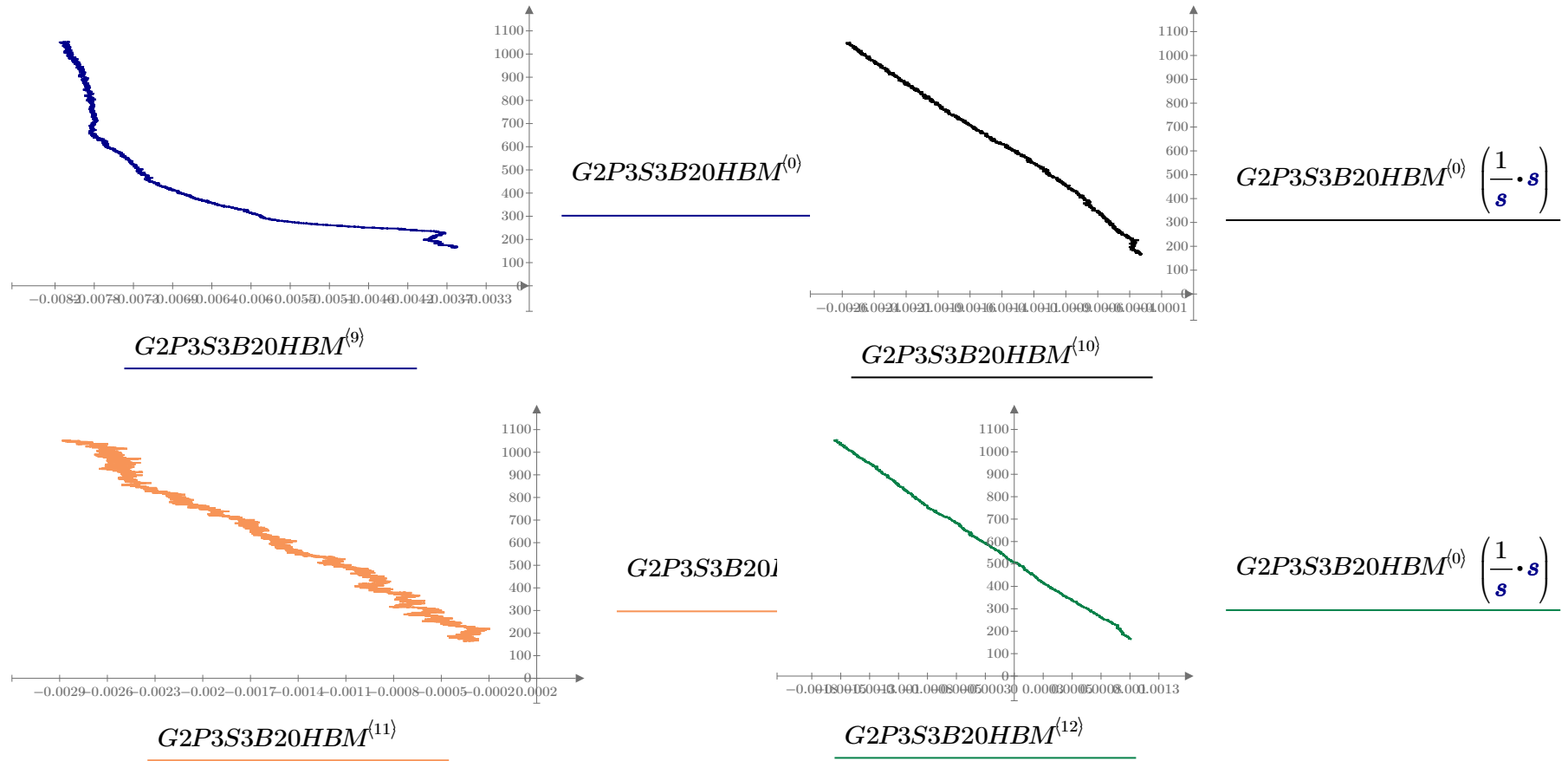


Fig J 1. Rawdata axial load time history for pile group 2P3S3B20

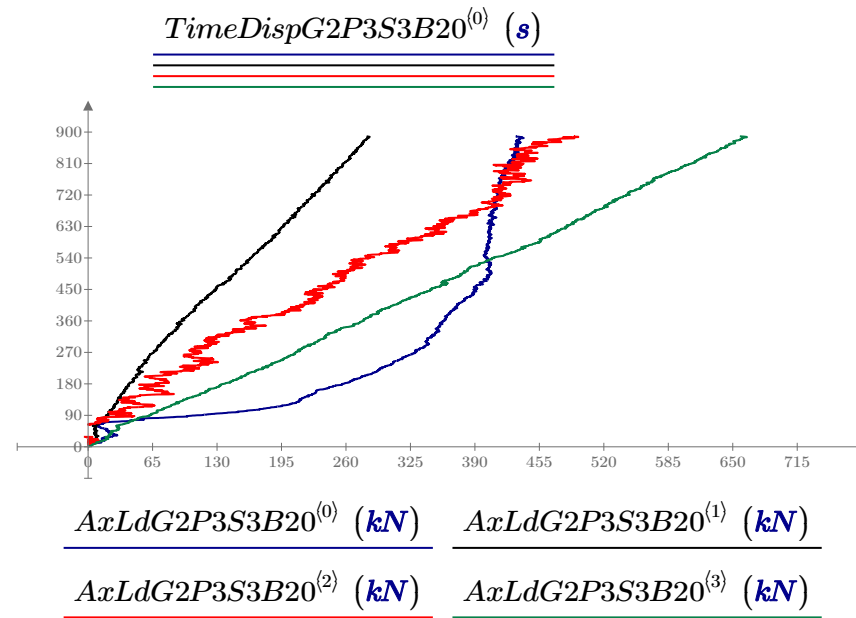


Fig J 2. Axial Load time history for pile group 2P3S3B20

Appendix J
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

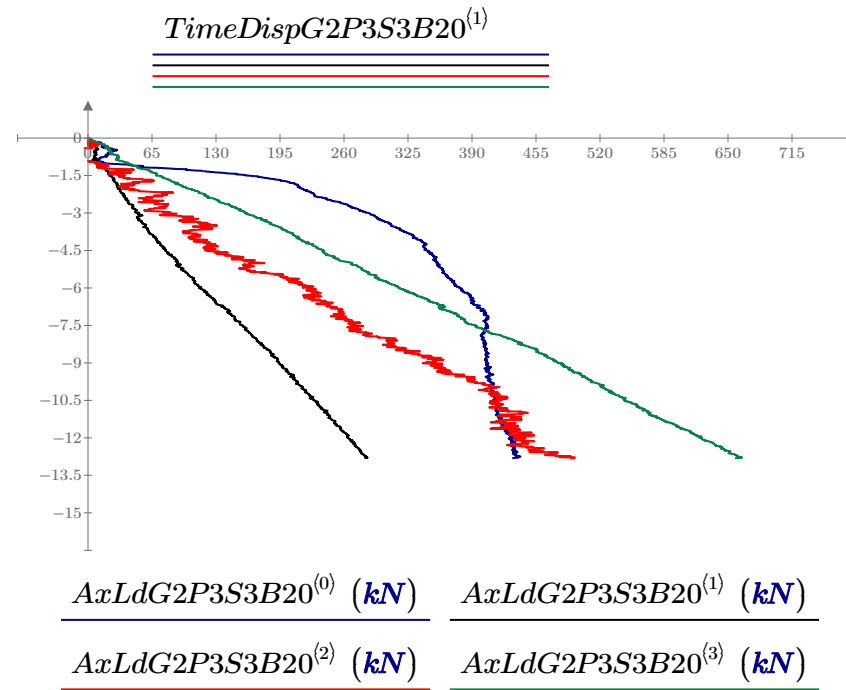


Fig J 3. Axial Load -displacement for pile group 2P3S3B20

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

Functions for determining the Q distribution profile at strain gauge location

TOL := 0.00000001

```
SGplotQP (AxLdG4P3S2B0 , TimeDispG4P3S2B0 , PileNum) :=
  QP0 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(0) , "near"))
  QP1 ← if PileNum = 0
    augment (lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-15 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-20 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  else
    augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(1) , "near"))
  QP2 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(2) , "near"))
  QP3 ← augment (lookup (-2.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-7.5 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near") , lookup (-10 , TimeDispG4P3S2B0(1) , AxLdG4P3S2B0(3) , "near"))
  combined ← if PileNum = 0
    stack (QP0 , QP1 , QP1 , QP1 , QP1 , QP1)
  else
    stack (QP0 , QP1 , QP1 , QP2 , QP2 , QP3)
  combined
```

$$Qdist2P3S3B20 := SGplotQP (AxLdG2P3S3B20 , TimeDispG2P3S3B20 , 3) = \begin{bmatrix} 247.2566 & 354.6181 & 404.126 & 411.4815 \\ 40.3548 & 90.665 & 157.5082 & 218.3071 \\ 40.3548 & 90.665 & 157.5082 & 218.3071 \\ 68.4741 & 179.5669 & 269.6345 & 414.254 \\ 68.4741 & 179.5669 & 269.6345 & 414.254 \\ 133.0392 & 267.947 & 392.391 & 523.9354 \end{bmatrix} \text{ kN}$$

$$SGEmbDP := - \begin{bmatrix} 0.6 + 3.5 & 0.6 + 3.5 \\ 0.6 & 0.6 + 2 \\ 0 & 0.6 + 2 \\ 0 & 0.6 + 1 \\ 0 & 0.6 + 1 \\ 0 & 0.6 \end{bmatrix} \cdot D \cdot Nscale^{selfac_{0,0}} \quad \begin{array}{l} SG \text{ embedment depth in prototype scale. Here, colm 0-4 represents} \\ P0 \text{ to P4. Row 0 to 5 represents depth to strain SG 1 to 4} \end{array}$$

Appendix J
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

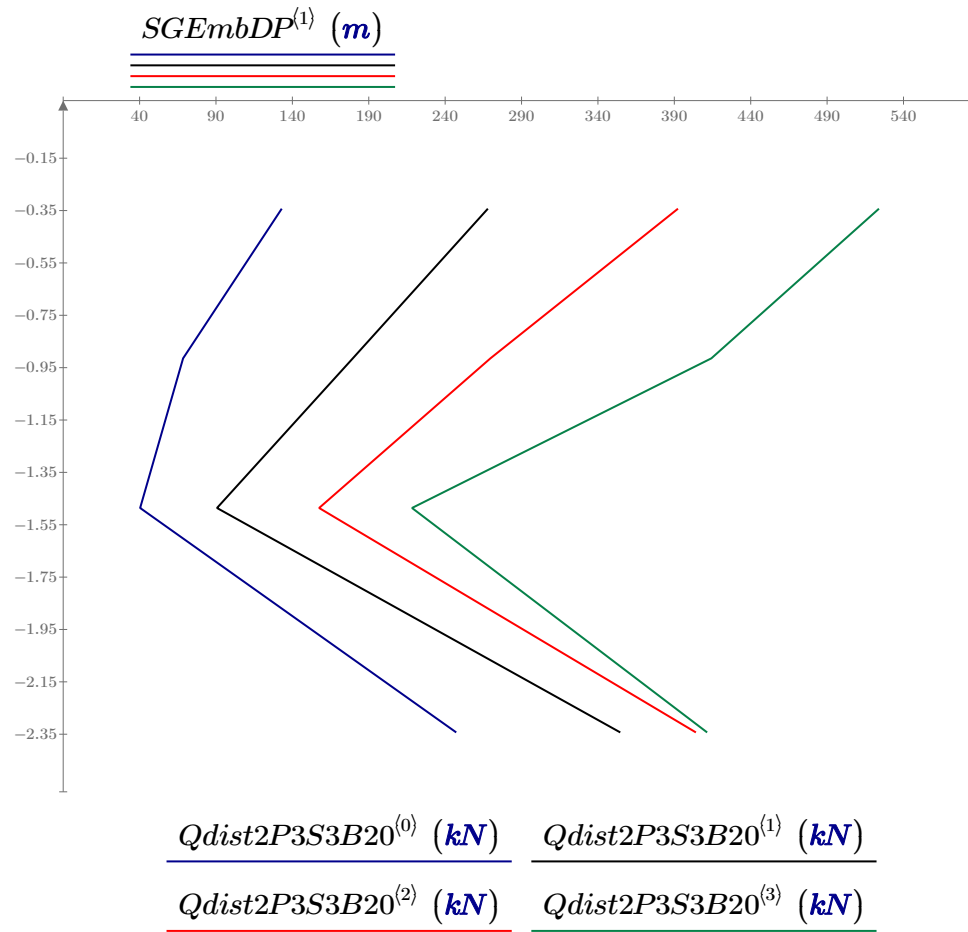
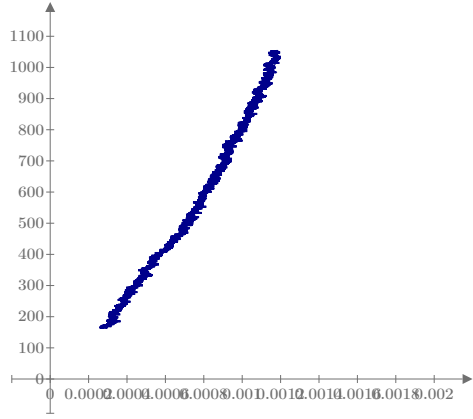


Fig J 4. Axial Load -depth for pile group 2P3S3B20

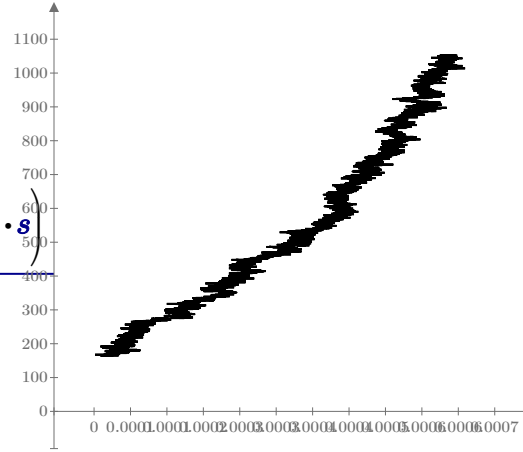
2.3.3 Bending Moment vs Time

$BM2G2P3S3B20 := ConvLd(G2P3S3B20HBM, 2, CFBM, 999, 3)$



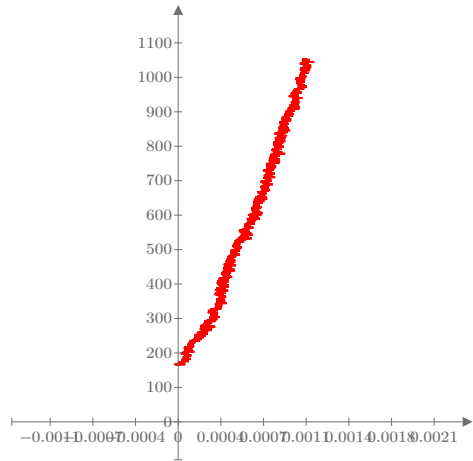
$G2P3S3B20HBM^{(5)}$

$G2P3S3B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



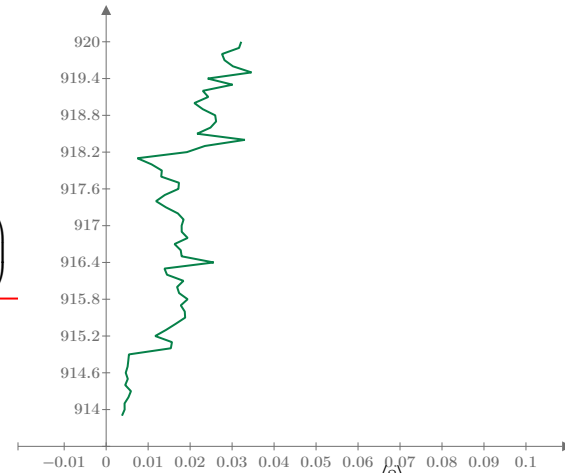
$G2P3S3B20HBM^{(6)}$

$G2P3S3B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G2P3S3B20HBM^{(7)}$

$G2P3S3B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$



$G2P3S3B20HBM^{(8)}$

$G2P3S3B20HBM^{(0)} \left(\frac{1}{s} \cdot s \right)$

Fig J 5. Raw Data Bending Moment 2 for pile group 2P3S3B20

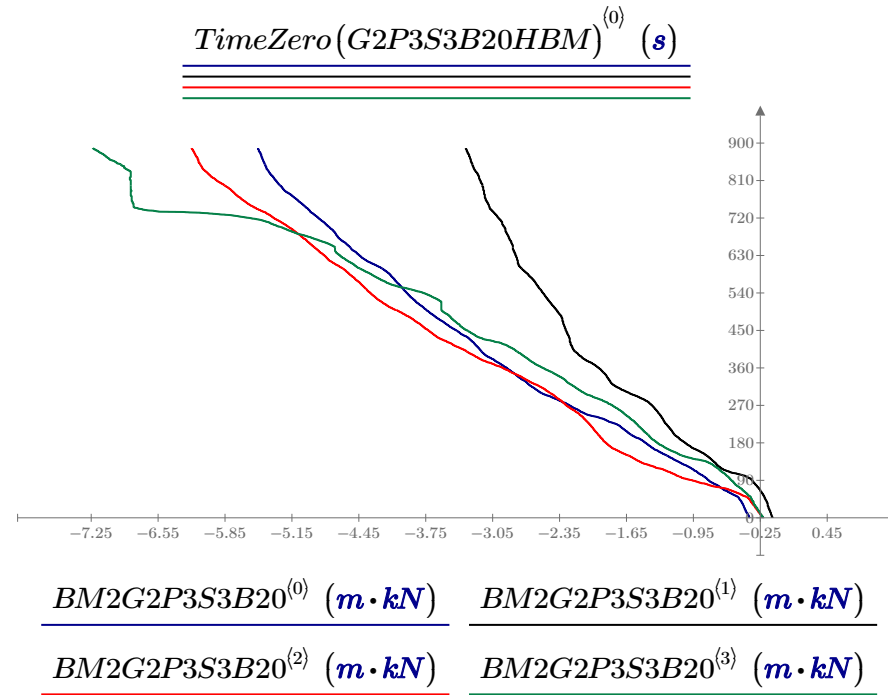


Fig J 6. Bending Moment 2 time history for pile group 2P3S3B20

Appendix J
Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

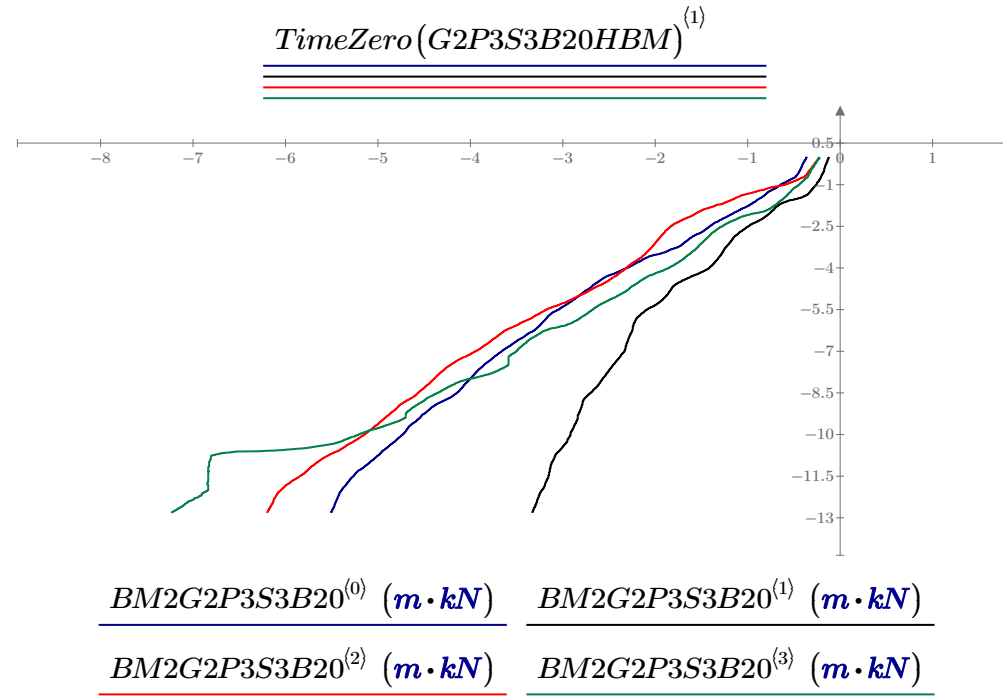


Fig J 7. Bending Moment 2 - displacement for pile group 2P3S3B20

$$BMMindist2P3S3B20 := SGplotQP(BM2G2P3S3B20, TimeDispG2P3S3B20, 3) = \begin{bmatrix} -1.4113 & -2.8226 & -3.857 & -4.7336 \\ -0.9922 & -1.8808 & -2.4589 & -2.9161 \\ -0.9922 & -1.8808 & -2.4589 & -2.9161 \\ -1.833 & -2.8248 & -4.2151 & -5.1449 \\ -1.833 & -2.8248 & -4.2151 & -5.1449 \\ -1.2763 & -2.4076 & -3.5872 & -5.2115 \end{bmatrix} m \cdot kN$$

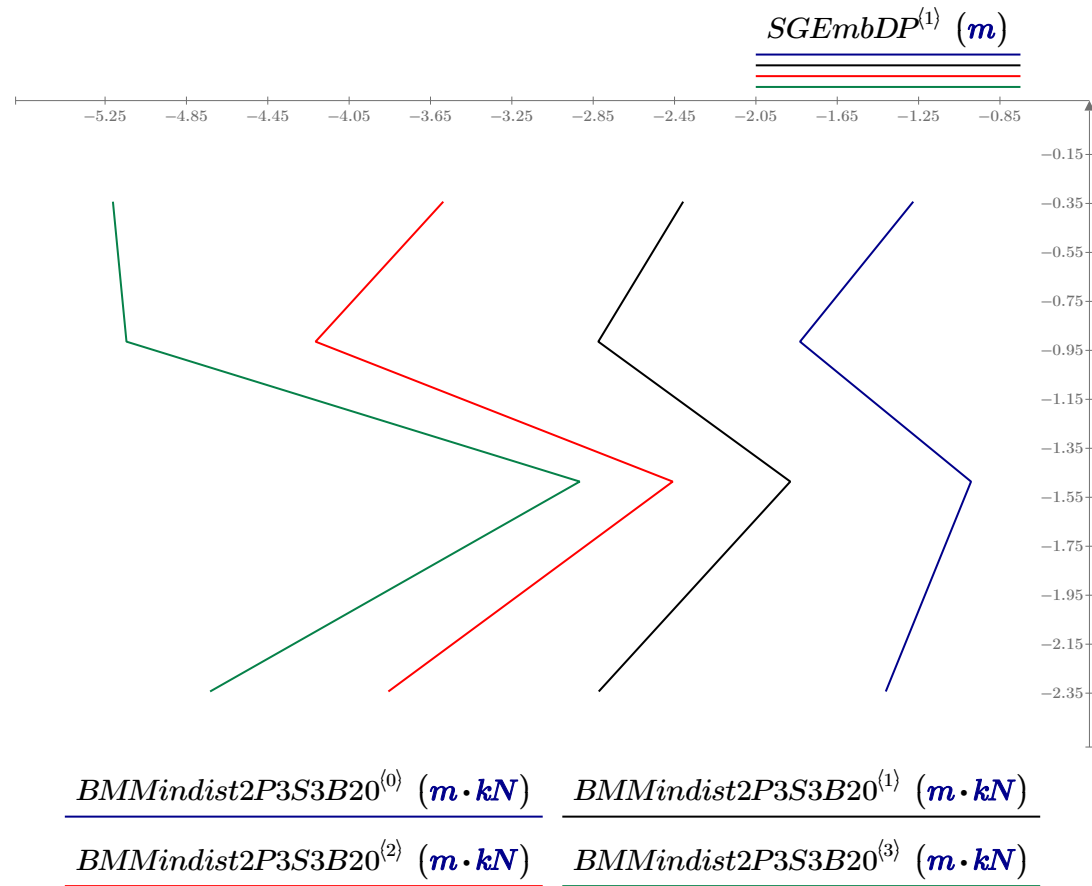


Fig J 8. Bending Moment 2 - depth for pile group 2P3S3B20

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

2.3.4 LVDT vs Time

Function for determining the time and displacement from LVDT

```

LVDT(LVDTRawData, smthn) :=
  TimeLVDT ← submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 0, 0) s
  LVDT1 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 1, 1) mm, smthn)
  LVDT2 ← medsmooth(submatrix(LVDTRawData, 0, rows(LVDTRawData) - 1, 2, 2) mm, smthn)
  for i ∈ 0, 1..rows(LVDTRawData) - 1
    k_i ← (TimeLVDT_i - TimeLVDT_0)
    q_i ← -(LVDT1_i - LVDT1_0) • 1.3 • Nscale scifac0,0
    m_i ← -(LVDT2_i - LVDT2_0) • 1.3 • Nscale scifac0,0
    n_i ← -(TimeLVDT_i - TimeLVDT_0) • CmpRate • Nscale scifac0,0
  augment(k, q, m, n)
  
```

$LVDTRawData := \text{READExcel}(\text{".\Nav-3P3B20D.xlsx"}, \text{"Sheet1 (2)!A2:C910"})$

$TimeLVDT := LVDT(LVDTRawData, 11)^{(0)}$ $LVDT1 := LVDT(LVDTRawData, 11)^{(3)}$

$LVDTL := LVDT(LVDTRawData, 11)^{(1)}$ $LVDT2 := LVDT(LVDTRawData, 11)^{(2)}$

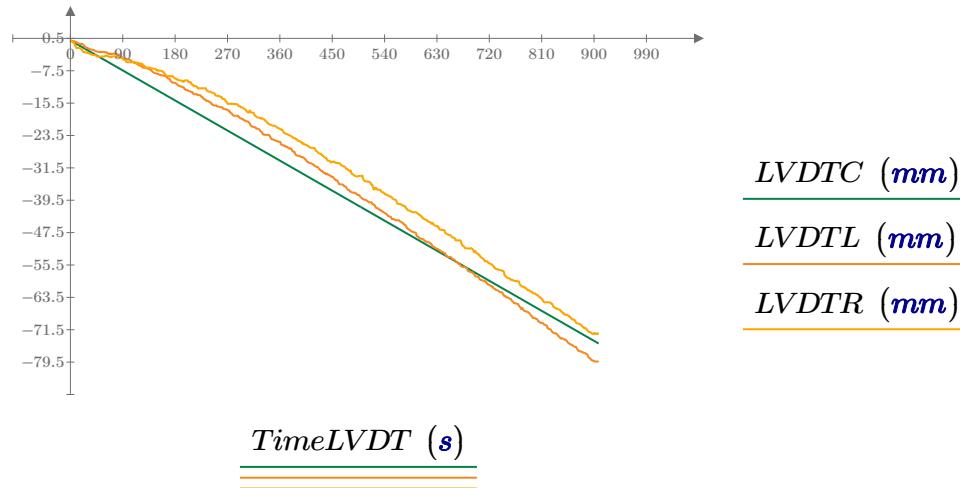


Fig J 9. LVDT displacements time history for pile group 2P3S3B20

Data Conversion and Processing Sheet for NI03 series of Centrifuge Tests on 2P3S3B20 Helix Pile Group

Function for determining the tilting of the plate

```

Tilt (SpacingDCDLR, SpacingDLDR) :=
  k ← (SpacingDCDLR) • mm • Nscalesclfac0,0
  q ← (SpacingDLDR) • mm • Nscalesclfac0,0
  for i ∈ 0, 1 .. rows (LVDTRawData) - 1
    mi ←  $\frac{(LVDTC_i - LVDR_i)}{k}$ 
    ni ←  $\frac{(LVDTC_i - LVDTL_i)}{k}$ 
    li ←  $\frac{(LVDR_i - LVDTL_i)}{q}$ 
  augment (m, n, l)
  
```

$Rot4P3S2B0 := \text{augment} \left(\text{medsmooth} \left(Tilt(7.1, 7.8)^{(0)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(1)}, 99 \right), \text{medsmooth} \left(Tilt(7.1, 7.8)^{(2)}, 99 \right) \right)$

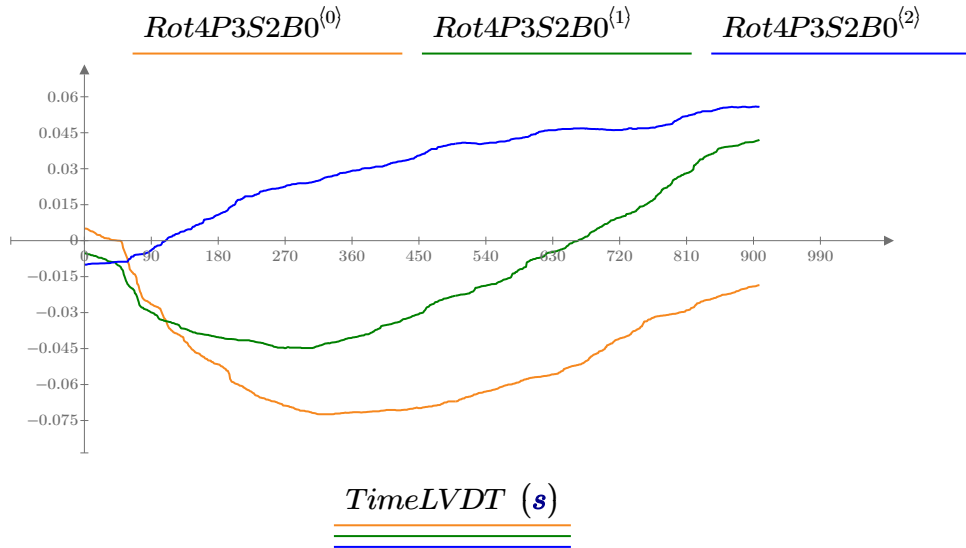


Fig J 10. LVDT rotations time history for pile group 2P3S3B20

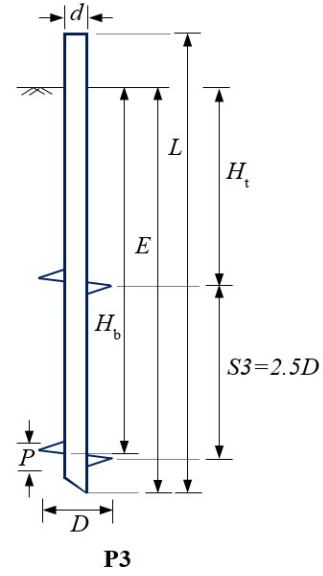
Appendix K

Ultimate Capacity and Installation Torque: Helical Piles in Sand

Pile Code: P3 Double Helix

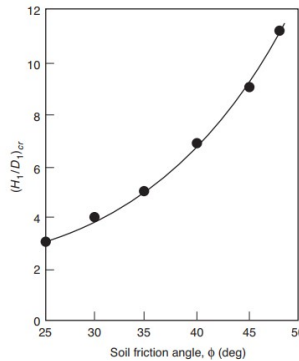
Properties of the Helical Pile:

Scale factor, $N := 20$ Number of Helices, $n := 2$
 Length of the Pile, $L := N \cdot 271.8 \text{ mm} = 5.436 \text{ m}$
 Diameter of the shaft, $d := N \cdot 12.7 \text{ mm} = 0.254 \text{ m}$
 Diameter of the helix, $D := N \cdot 38.1 \text{ mm} = 0.762 \text{ m}$
 Embedment depth of pile, $E := N \cdot 169.1 \text{ mm} = 3.382 \text{ m}$
 Depth to bottom helix, $H_b := N \cdot 150 \text{ mm} = 3 \text{ m}$
 Perimeter of the Helical Pile Shaft, $P_s := \pi \cdot D = 2.394 \text{ m}$
 Effective Shaft Length, $H_{eff} := (H_b - D) = 2.238 \text{ m}$
 Pitch of the helix, $P := N \cdot 12.7 \text{ mm} = 0.254 \text{ m}$
 Average Helix Diameter, $D_a := D$
 Net area of the helix, $A_b := \pi \cdot \frac{(D^2 - d^2)}{4} = 0.405 \text{ m}^2$
 Net area of the top helix, $A_t := A_b = 0.405 \text{ m}^2$
 Spacing between two helices, $S3 := 2.5 \cdot D = 1.905 \text{ m}$
 Depth to pile helix, $H := H_b = 3 \text{ m}$
 Pile section length in the soil layer, $\Delta L := 3 \text{ m}$ Ratio, $\frac{H_{eff}}{D_a} = 2.937$
 Thickness of the Helix, $t := N \cdot 1.25 \text{ mm} = 0.025 \text{ m}$
 Pile Spacing, $S := 0 \text{ m}$
 Depth to top helix, $H_t := H_b - S3 = 1.095 \text{ m}$

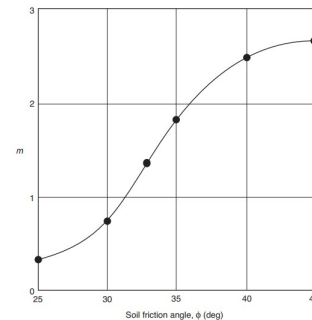


Properties of the Sand:

Effective Unit Weight of Soil, $\gamma' := 20 \frac{\text{kN}}{\text{m}^3}$ Peak Friction Angle, $\varphi_{peak} := 38 \text{ deg}$
 Coefficient of lateral earth pressure in compression loading, $K_s := 0.09 \cdot e^{0.08 \cdot \left(\varphi_{peak} \cdot \frac{180}{\pi} \right)}$ Perko (2009) = 1.881
 Meyerhof (1951); Meyerhof and Adams (1968);
 Dimensionless Bearing Capacity factor, $N_q := e^{\pi \cdot \tan(\varphi_{peak})} \cdot \tan\left(\frac{\pi}{180} \cdot \left(45 + \frac{\varphi_{peak} \cdot \frac{180}{\pi}}{2}\right)\right) = 48.933$
 $N_{\gamma} := (N_q - 1) \cdot \tan(1.4 \cdot \varphi_{peak}) = 64.074$ $N'_q := 45$
 $\delta := \left(\frac{3}{4} \cdot \varphi_{peak}\right) = 28.5 \text{ deg}$ $N_{\gamma v} := 2 \cdot (N_q + 1) \cdot \tan(\varphi_{peak}) = 78.024$



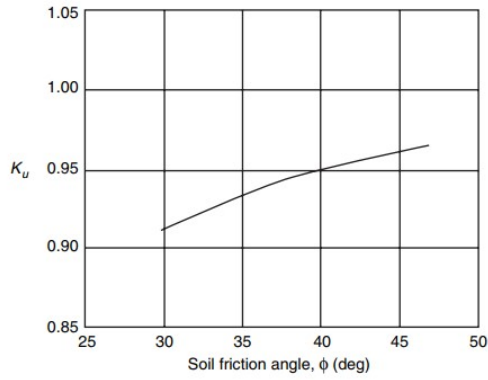
Variation of $(H/D)_{cri}$ with soil friction angle (Das et al 1990)



Variation of m with soil friction angle (Das et al 1990)

Critical ratio from Graph 1, **Critical** := 4 Values of m from Graph 2, **m1** := 0.75
 Das and Seeley (1975)

Breakout Factor, $F_q := 1 + \left(2 \cdot \left(1 + m1 \cdot \left(\frac{H_{eff}}{D_a}\right)\right) \cdot \frac{H_{eff}}{D_a} \cdot K_s \cdot \tan(\varphi_{peak})\right) = 28.655$



Variation of k with friction angle

$$R = \begin{cases} 2.255 - 0.0426\phi & \text{for } 45^\circ \geq \phi \geq 30^\circ \text{ with } 15^\circ \geq \psi \geq 0^\circ \text{ and } D \geq 500 \text{ mm} \\ 1.0 & \text{for } \phi < 30^\circ \text{ and } \psi = 0^\circ \end{cases}$$

Elsherbiny et al (2013)

$$E_H := 0.25$$

$$R := \begin{cases} 45 \text{ deg} \geq \varphi_{peak} \geq 30 \text{ deg} \\ \left\| 2.255 - \left(0.0426 \cdot \varphi_{peak} \cdot \frac{180}{\pi} \right) \right\| \\ \text{else if } \varphi_{peak} < 30 \text{ deg} \\ \left\| 1 \right\| \end{cases} = 0.636$$

Hoyt and Clemence (1989)

$$k_T := 2 \cdot 5 \frac{1}{m}$$

$$T := 53.554 \text{ (kN} \cdot \text{m)}$$

Estimation of Ultimate Compression Capacity

Mitsch and Clemence (1985)

Ultimate Compression Capacity,

$$Q_{c1} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot \pi \cdot D \cdot \gamma' \cdot (H_b^2 - H_t^2) \cdot K_s \cdot \tan(\varphi_{peak}) \right) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot \tan(\varphi_{peak}) \cdot H_{eff}^2 \right) + (\gamma' \cdot H_t \cdot A_t \cdot N_q)$$

$$Q_{c1} = 2075.32 \text{ kN}$$

Das (1990)

For Shallow Piles

$$Q_{c2a} := (\gamma' \cdot H_b \cdot A_b \cdot F_q) + \left(\frac{1}{2} \cdot \pi \cdot D \cdot \gamma' \cdot (H_b^2 - H_t^2) \cdot K_s \cdot \tan(\varphi_{peak}) \right) + (\gamma' \cdot H_t \cdot A_t \cdot F_q) = (1.226 \cdot 10^3) \text{ kN}$$

For Deep Piles

$$Q_{c2b} := (\gamma' \cdot H_b \cdot A_b \cdot F_q) + \left(\frac{1}{2} \cdot \pi \cdot D \cdot \gamma' \cdot (H_b^2 - H_t^2) \cdot K_s \cdot \tan(\varphi_{peak}) \right) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot \tan(\varphi_{peak}) \cdot H_{eff}^2 \right) + (\gamma' \cdot H_t \cdot A_t \cdot F_q) = (1.402 \cdot 10^3) \text{ kN}$$

$$Q_{c2} := \begin{cases} \text{if } \frac{H_{eff}}{D_a} > \text{Critical} \\ \left\| Q_{c2a} \right\| \\ \text{else if } \frac{H_{eff}}{D_a} < \text{Critical} \\ \left\| Q_{c2b} \right\| \end{cases}$$

Ultimate Compression Capacity,

$$Q_{c2} = 1402.08 \text{ kN}$$

Adams and Khym (1972)

$$Q_{c3} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot \tan(\varphi_{peak}) \cdot H_{eff}^2 \right) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) = (1.801 \cdot 10^3) \text{ kN}$$

Chance (1993)

$$Q_{c4} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) = (1.625 \cdot 10^3) \text{ kN}$$

Stephenson (1997)

$$Q_{c5} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot \gamma' \cdot D \cdot A_b \cdot N_\gamma \right) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot H_{eff}^2 \right) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) + \left(\frac{1}{2} \cdot \gamma' \cdot D \cdot A_t \cdot N_\gamma \right) = (2.246 \cdot 10^3) \text{ kN}$$

Nasr (2004)

$$Q_{c6a} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot \pi \cdot D \cdot \gamma' \cdot (H_b^2 - H_t^2) \cdot K_s \cdot \tan(\varphi_{peak}) \right) + (\gamma' \cdot H_t \cdot A_b \cdot N_q)$$

$$Q_{c6} := \left\| \begin{array}{l} \text{if } \frac{H_{eff}}{D_a} > 5 \\ \quad \left\| \begin{array}{l} \text{"Not Applicable"} \\ \text{else if } \frac{H_{eff}}{D_a} \leq 5 \\ \quad \left\| Q_{c6a} \end{array} \right. \end{array} \right\|$$

Ultimate Compression Capacity,

$$Q_{c6} = 1899.07 \text{ kN}$$

CFEM (2006)

$$\sigma'_v := \gamma' \cdot E$$

$$Q_{c7} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot \gamma' \cdot D \cdot A_b \cdot N_\gamma \right) + (\pi \cdot d \cdot L \cdot \sigma'_v \cdot K_s \cdot \tan(\delta)) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) + \left(\frac{1}{2} \cdot \gamma' \cdot D \cdot A_t \cdot N_\gamma \right) = 2320.12 \text{ kN}$$

Perko (2009)

$$Q_{c8} := (N_q' - 1) \cdot 2 \cdot D \cdot \gamma' \cdot A_b + (N_q' - 1) \cdot 2 \cdot D \cdot \gamma' \cdot A_t = (1.09 \cdot 10^3) \text{ kN}$$

Elsherbiny et al (2013)

$$Q_{c9} := (\gamma' \cdot H_b \cdot A_b \cdot N_q \cdot R) + (E_H \cdot \gamma' \cdot H_b \cdot A_b \cdot N_q \cdot R) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot \tan(\varphi_{peak}) \cdot H_{eff}^2 \right) \downarrow = (1.47 \cdot 10^3) \text{ kN} \\ + (\gamma' \cdot H_t \cdot A_t \cdot N_q \cdot R) + (E_H \cdot \gamma' \cdot H_t \cdot A_t \cdot N_q \cdot R)$$

Elkasabgy et al (2015)

$$Q_{c10} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot P_s \cdot K_s \cdot \gamma' \cdot \tan(\varphi_{peak}) \cdot H_{eff}^2 \right) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) = (1.8 \cdot 10^3) \text{ kN}$$

George et al (2017)

$$Q_{c11} := (0.5 \cdot \gamma' \cdot H_b \cdot A_b \cdot \tan(\delta)) + (0.7 \cdot \gamma' \cdot H_b \cdot A_b \cdot N_q) + (0.274 \cdot \gamma' \cdot D \cdot A_b \cdot N_{\gamma v}) \downarrow = (1.41 \cdot 10^3) \text{ kN} \\ + (0.5 \cdot \gamma' \cdot H_t \cdot A_t \cdot \tan(\delta)) + (0.7 \cdot \gamma' \cdot H_t \cdot A_t \cdot N_q) + (0.274 \cdot \gamma' \cdot D \cdot A_t \cdot N_{\gamma v})$$

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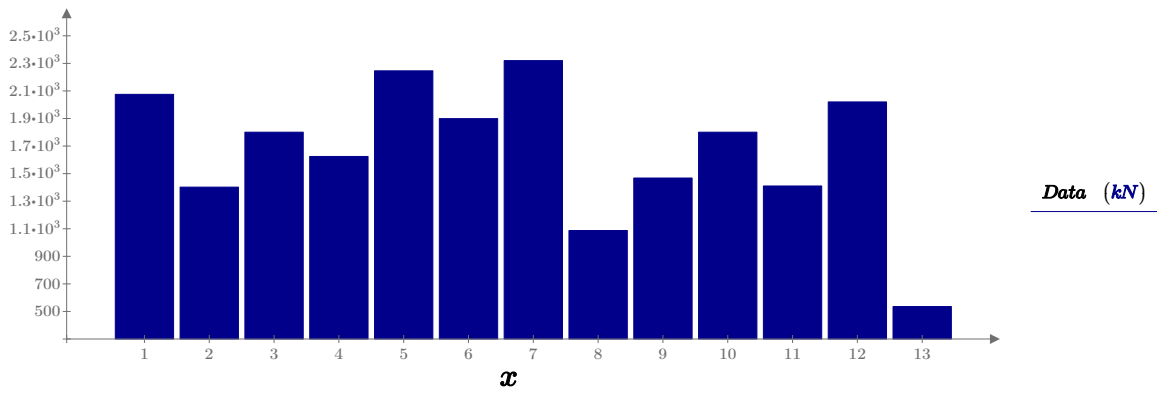
$$Q_{c12} := (\gamma' \cdot H_b \cdot A_b \cdot N_q) + \left(\frac{1}{2} \cdot D \cdot \gamma' \cdot A_b \cdot N_\gamma \right) + (\gamma' \cdot H_t \cdot A_t \cdot N_q) + \left(\frac{1}{2} \cdot D \cdot \gamma' \cdot A_t \cdot N_\gamma \right) = (2.02 \cdot 10^3) \text{ kN}$$

Hoyt and Clemence (1989)

$$Q_{c13} := k_T \cdot T = 535.54 \text{ kN}$$

$$Data := \begin{bmatrix} Q_{c1} \\ Q_{c2} \\ Q_{c3} \\ Q_{c4} \\ Q_{c5} \\ Q_{c6} \\ Q_{c7} \\ Q_{c8} \\ Q_{c9} \\ Q_{c10} \\ Q_{c11} \\ Q_{c12} \\ \vdots \end{bmatrix} = \begin{bmatrix} 2.075 \cdot 10^3 \\ 1.402 \cdot 10^3 \\ 1.801 \cdot 10^3 \\ 1.625 \cdot 10^3 \\ 2.246 \cdot 10^3 \\ 1.899 \cdot 10^3 \\ 2.32 \cdot 10^3 \\ 1.087 \cdot 10^3 \\ 1.468 \cdot 10^3 \\ 1.801 \cdot 10^3 \\ 1.41 \cdot 10^3 \\ 2.02 \cdot 10^3 \\ \vdots \end{bmatrix} \text{ kN } x := 1 \dots 13 = \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ \vdots \end{bmatrix}$$

$$\sigma := \text{Stdev}(Data) = 494.696 \text{ kN}$$



Installation Torque

Ghaly and Hanna (1991)

Total Unit wt of soil $\gamma := 20 \frac{kN}{m^3}$

$D_i := D = 0.762 \text{ m}$

$\phi := \varphi_{peak} = 38 \text{ deg}$

$A_{bi} := A_t = 0.405 \text{ m}^2$

$p := P = 254 \text{ mm}$

Coefficient of Passive Earth Pressure

$K_p := \frac{(1 + \sin(\phi))}{(1 - \sin(\phi))} = 4.204$

$\delta := \frac{3}{4} \cdot \phi = 28.5 \text{ deg}$

Helix angle of the helical shaped screw unit

$\psi := \text{atan}\left(\frac{p}{(\pi \cdot D_i)}\right) = 6.057 \text{ deg}$

Modified Coefficient of Passive Earth Pressure

$K'_p := 0.3 \cdot K_p = 1.261$

$\frac{p}{\pi \cdot D_i} = 0.106$

Coefficient of Active Earth Pressure

$K_a := \frac{(1 - \sin(\phi))}{(1 + \sin(\phi))} = 0.238$

$t = 25 \text{ mm}$

Coefficient of Friction between the anchor's shaft and the soil

$K_f := \tan(\delta) = 0.543$

Lateral Force acting on the helix $F := 0.5 \cdot \gamma \cdot H_b \cdot K_p \cdot p \cdot (1 \text{ m} + (p)) + 0.5 \cdot \gamma \cdot H_t \cdot K_p \cdot p \cdot (1 \text{ m} + (p)) = 54.83 \text{ kN}$

Resisting Moment on Shaft, $T_1 := 0.5 \cdot \gamma \cdot (H_b)^2 \cdot \cos(\delta) \cdot K'_p \cdot K_f \cdot \pi \cdot d \cdot \left(\frac{d}{2}\right) = 5.488 \text{ kN}\cdot\text{m}$

Resisting Moment on Helix Shaft Diameter,

$T_2 := 0.5 \cdot \gamma \cdot (H_b)^2 \cdot \sin(\delta) \cdot K'_p \cdot \tan(\delta + \psi) \cdot \pi \cdot d \cdot \left(\frac{d}{2}\right) = 3.78 \text{ kN}\cdot\text{m}$

Resisting Moment on Helix Diameter,

$T_3 := 0.5 \cdot \gamma \cdot (H_b)^2 \cdot \sin(\phi) \cdot K'_p \cdot \tan(\delta + \psi) \cdot \pi \cdot D_i \cdot \left(\frac{D_i}{2}\right) \downarrow = 49.744 \text{ kN}\cdot\text{m}$
 $+ 0.5 \cdot \gamma \cdot (H_t)^2 \cdot \sin(\phi) \cdot K'_p \cdot \tan(\delta + \psi) \cdot \pi \cdot D_i \cdot \left(\frac{D_i}{2}\right)$

Resisting Moment at Upper Side of Helix

$T_4 := \gamma \cdot (H_b) \cdot K_a \cdot A_b \cdot \tan(\delta + \psi) \cdot \left(\frac{(D_i + d)}{4}\right) + \gamma \cdot (H_t) \cdot K_a \cdot A_t \cdot \tan(\delta + \psi) \cdot \left(\frac{(D_i + d)}{4}\right) = 1.382 \text{ kN}\cdot\text{m}$

Resisting Moment at Lower Side of Helix

$T_5 := \gamma \cdot (H_b) \cdot K_p \cdot A_{bi} \cdot \tan(\delta + \psi) \cdot \left(\frac{(D_i + d)}{4}\right) + \gamma \cdot (H_t) \cdot K_p \cdot A_t \cdot \tan(\delta + \psi) \cdot \left(\frac{(D_i + d)}{4}\right) = 24.415 \text{ kN}\cdot\text{m}$

Resisting Moment Bearing Force Entire Height

$T_6 := F \cdot \left(\frac{(D_i - d)}{8}\right) = 3.482 \text{ kN}\cdot\text{m}$

Resisting Moment acting on outer perimeter of Helix Thickness

$T_7 := \gamma \cdot H_b \cdot K_p \cdot K_f \cdot (\pi \cdot D_i) \cdot \left(\frac{D_i}{(2)}\right) \cdot t + \gamma \cdot H_t \cdot K_p \cdot K_f \cdot (\pi \cdot D_i) \cdot \left(\frac{D_i}{(2)}\right) \cdot t = 4.262 \text{ kN}\cdot\text{m}$

Installation Torque

$T_{-1} := T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 = (9.26 \cdot 10^4) \text{ N}\cdot\text{m}$

Tsuha and Aoki (2010)

Relationship Between Uplift Capacity and Installation Torque for Deep Helical Piles in Sand

$d_c := \frac{2}{3} \cdot \frac{(D_i^3 - d^3)}{(D_i^2 - d^2)} = 0.55 \text{ m}$ $\theta := \text{atan}\left(\frac{p}{(\pi \cdot d_c)}\right) = 8.358 \text{ deg}$

$A_h := A_b = 0.405 \text{ m}^2$

$\sigma'_v := \gamma \cdot E = 67.64 \text{ kPa}$

$D_{hj} := H_b = 3 \text{ m}$

$q_s := \sigma'_v \cdot K_s \cdot \tan(\delta) = 69.098 \text{ kPa}$

$F_q = 28.655$

$Q_s := \pi \cdot d \cdot L \cdot q_s = 299.729 \text{ kN}$ $Q_h := (A_b \cdot \gamma \cdot H_b \cdot F_q) + (A_t \cdot \gamma \cdot H_t \cdot F_q) = 951.316 \text{ kN}$

$T_{-2} := \frac{(Q_s \cdot d)}{2} + \frac{(Q_h \cdot d_c \cdot \tan(\theta + \delta))}{2} = (2.343 \cdot 10^5) \text{ N}\cdot\text{m}$

Sakr (2015)

Developed theoretical torque model using installation records collected from different sites

$$D_{h1} := H_t \quad D_{hj'} := H_t \quad t_j := t \quad \sigma'_{vj} := \gamma' \cdot H_b = 60 \text{ kPa}$$

Torsional Moment on Pile Shaft

$$T_1 := \sigma'_v \cdot D_{h1} \cdot \cos(\delta) \cdot K_p \cdot K_f \cdot \pi \cdot \frac{d^2}{4} = 7.528 \text{ kN} \cdot \text{m}$$

Torsional Moment Component of the Helices

$$T_{2j} := \sigma'_{vj} \cdot (D_{hj} - D_{hj'}) \cdot \sin(\delta) \cdot K_p \cdot \tan(\delta + \psi) \cdot \pi \cdot \frac{d^2}{4} = 8.001 \text{ kN} \cdot \text{m}$$

$$T_{3j} := \sigma'_{vj} \cdot (D_{hj} - D_{hj'}) \cdot \sin(\delta) \cdot K_p \cdot \tan(\delta + \psi) \cdot \pi \cdot \frac{D_i^2}{4} = 72.011 \text{ kN} \cdot \text{m}$$

$$T_{4j} := \sigma'_{vj} \cdot K_a \cdot \tan(\delta + \psi) \cdot \pi \cdot \frac{(D_i^3 - d^3)}{12} = 1.097 \text{ kN} \cdot \text{m}$$

$$T_{5j} := \sigma'_{vj} \cdot K_p \cdot \tan(\delta + \psi) \cdot \pi \cdot \frac{(D_i^3 - d^3)}{12} = 19.377 \text{ kN} \cdot \text{m}$$

$$T_{6j} := \sigma'_{vj} \cdot K_p \cdot p \cdot \tan(\phi) \cdot \pi \cdot \frac{(D_i^2)}{2} = 45.652 \text{ kN} \cdot \text{m}$$

$$T_{7j} := \sigma'_{vj} \cdot K_p \cdot t_j \cdot K_f \cdot \pi \cdot \frac{(D_i^2)}{2} = 3.123 \text{ kN} \cdot \text{m}$$

$$T_{8j} := (D_i - d) \cdot N_q \cdot t_j \cdot \sigma'_{vj} \cdot \frac{(D_i + d)}{4} = 9.471 \text{ kN} \cdot \text{m}$$

Installation Torque

$$T_{-3} := T_1 + (T_{2j} + T_{3j} + T_{4j} + T_{5j} + T_{6j} + T_{7j} + T_{8j}) = 166.26 \text{ kN} \cdot \text{m}$$

Mean Torque

$$\mu_T := \text{mean}(T_{-1}, T_{-2}, T_{-3}) = 164.373 \text{ kN} \cdot \text{m}$$

$$\text{ModelScale} := \frac{\mu_T}{N^3} = 20.547 \text{ N} \cdot \text{m}$$